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A RADIOGRAPHIC LAYER COUNTER FOR COMPOSITES

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The Army helmet is a composite of layers of resin-bonded Kevlar. Inadvertent omission of layers or undetected shifting of layers during molding processes can reduce the effective number of fibers in some helmet areas and impair their strength properties. A nondestructive method of 100% testing of the helmets, more effective than random sampling by ballistic testing, is needed. This six-month study evaluated the feasibility of using relatively low-energy radioisotopes to guage the uniformity of Kevlar helmets. The potential for constructing a portable detection unit was also assessed. A laboratory radiometric test system was used to evaluate resin-bonded Kevlar samples, as well as actual Army helmets from current suppliers. It was found that the radiometric test system has the capacity to reflect the general condition of fabricated Kevlar helmets.

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Variation of radiation transmission characteristics were readily discernible as a result of changes in the number of layers which were contained in simulated helmet configurations, the relative degree of resin present in localized areas of Kevlar samples, as well as differences in the uniformity of the layering within rejected helmets. However, correlation of these test results with statistically-valid ballistics performance characteristics have still to be determined. This study indicates that a comprehensive performance evaluation of typical production helmets to develop accept/reject criteria, using our optimum radiation source and detection apparatus, should be conducted. The results would lead to the development of a field-operable system for helmet testing.

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PREFACE

This final report describes the research performed in the Phase I portion of the Small Business Innovative Research (SBIR) project "A Radiographic Layer Counter for Composites." The purpose of the research was to evaluate the feasibility of detecting the absence of one or more layers of Kevlar composite in as-manufactured US Army ballistic helmets. The specific technique under investigation was x-radiometry, using a low-energy radionuclide source and scintillation detector with associated electronics instrumentation.

Funding for this research was provided under contract number DAAK60-87-C-0039, issued by the Department of the Army, US Army Troop Support Command, Natick Research, Development and Engineering Center (NRDEC), Natick, Massachusetts, 01760-5011. The period of performance was June 30, 1987 through February 15, 1988. Technical monitoring of this research for the Department of the Army was performed by Project Managers Ms. Jane Astle and Mr. Stanley Waclawik of NRDEC in Natick, Massachusetts.

The research was conducted at Reinhart & Associates, Inc., Austin, Texas. Principal Investigator for this project was Dr. Ronald Larsen, the author of this report. Dr. Matthew Golis assisted Dr. Larsen in writing this report, contributing significantly in matters related to quality control, sampling techniques, and product reliability. Technical assistance was provided by Mr. Chris Vehrs. Editorial assistance was provided by Dr. Zirka Kaulbach. Consultants for this project were Dr. Thomas Bauers, of the University of Texas at Austin and Mr. Richard Savage. Ms. Vicki Childers typed the manuscript and Mr. Les Olinger provided computer-generated graphics, including line illustrations. Messrs. Chris Vehrs, Russell Childers, and Stanley Kaminski were our photographers.

The author and Reinhart & Associates, Inc. thank Mr. Tim Browder, of Unicore Federal Prison Industries, Mr. B. J. Richmond, of Devil's Lake Sioux Manufacturing Company, and Mr. Henry Tracy, of Geonautics, Inc., who furnished Kevlar helmets and test panels for this research free-of-charge, and provided a wealth of background information and helpful advice. Mr. Gene Lewis, of Lewcott Chemicals furnished samples of phenolic resin and Kevlar fabric on very short notice, and we are grateful for his help.

The author extends special notes of thanks to Mr. Eugene Reinhart, President of Reinhart & Associates, Inc., for his insight and encouragement, and to Mr. John Porter, Director of Engineering, for his objectivity, his willingness to act as a sounding board for the author, and his many useful suggestions throughout the course of this research.

A Radiographic Layer Counter for Composites

INTRODUCTION

This is the final report on the project "Radiographic Layer Counter for Composites," Contract DAAK60-87-C-0039, addressing the development of a nondestructive examination methodology to reliably determine the conformance of Kevlar®* composite military helmets with their component specifications. It summarizes the technical findings of a six-month project under the DOD Small Business Innovative Research (SBIR) program. The SBIR program is devoted to the creation and development of concepts that have been submitted from the small business community.

This SBIR project specifically addresses the use of relatively low energy radioisotopes for the gauging of the uniformity of Kevlar helmets. The purpose of the study was to assess the potential for constructing a field-operable unit during the second phase of the SBIR program (Phase II). This potential was to be determined through an experimental evaluation of the transmission characteristics of commercially available radioisotopes, which emit radiation in the low end of the available electromagnetic energy spectrum.

Performance characteristics of a potential configuration were to be evaluated on any available fabricated Kevlar helmets, both with and without rejectable defects contained therein.

The ultimate purpose of the study was to define clearly the needed operating characteristics of a radiometric system that would assure the US Army of quality control for fabricated helmets.

In defining these characteristics and in describing the test equipment and results in this report, we have elected to use US Customary units rather than standard International (SI) units because of their nearly-universal use by nondestructive evaluation specialists and manufacturers of radiographic and radiometric equipment in this country.

BACKGROUND

The Army helmet is a composite of layers of resin-bonded Kevlar®. During the manufacturing process, the positions of the layers will sometimes shift, leaving portions of the helmet with less protection than the design of the helmet was intended to provide. Presently, the only way to test the helmets is through destructive ballistic testing of randomly selected helmets from each lot. This process both wastes helmets and fails to provide thorough testing. A need exists to develop a nondestructive method of 100% testing of the helmets as they are produced.

In response to this need, the US Army Natick Research, Development & Engineering Center solicited proposals to develop a hand-held instrument possibly using radiographic energy sources to determine the number of layers of Kevlar at any particular location in the helmet.

*A product of the DuPont Corporation.

Preliminary consideration of the problem indicated that low energy penetrating radiation (less than 30 keV) would experience a large drop in its intensity while passing through materials exhibiting the attenuation characteristics of Kevlar and having the expected thicknesses found in Army helmets. This characteristic held the promise of being sufficiently unique to be quantitatively correlated with the localized absence of composite material. However, because homogeneity of the test materials is a strong factor in the usefulness of radioisotopic gauging, there was concern regarding just how well the radiation measured through typical helmet materials could be correlated with the existence of localized absences of reinforcing cloth, binding resins, and other deviations from helmet fabrication specifications.

Reinhart & Associates, Inc. (R&A) proposed a program in which the following objectives were to be addressed during the six-month duration of a typical SBIR Phase I research program.

- Definition of minimum acceptance criteria (performance and radiation safety).
- Fabrication of test specimens (through current suppliers of Army helmets), representative of potential problem areas within a typical Kevlar helmet.
- Design (identification) of laboratory instrumentation which would be representative of the performance capabilities of field portable units developed specifically for in-plant and receiving inspection applications.
- Assembly of the instruments for technical and operational evaluations intended to simulate typical use environments.
- Bench testing of the instrumentation assembly.
- Evaluation of the system's capability to discriminate between various ratios of fiber-to-resin concentrations.
- Testing of the assembled system at fabricator facilities.

Preliminary tests conducted at R&A produced successful radiographs showing differences in recorded density patterns on Type M film equipped with intensifying screens and exposed to radiation in the 25-keV range. The variations in density correlated with the removal of a single layer of Kevlar in a composite sample containing 16 layers as well as the addition of a single sheet of prepreg material to an 18-layer test sample. Similar results were obtained with a Cd^{109} source while using a Geiger-Mueller detector; however, the distinction between the addition and removal of a single layer was less clearly evident in the differences in output reading.

These preliminary assessments indicated the potential for using radiometric approaches to thickness gauging in Kevlar materials. However, the operating characteristics of potential systems would need to be carefully evaluated before a final recommendation for a field operable system could be made. Variables such as thickness sensitivity, lateral resolution, signal-to-noise ratios, and statistical deviations due to variances in helmet configuration, among others, would have to be assessed prior to selecting the optimum equipment-procedure combination which would yield the most statistically-valid assessment of helmet integrity.

PROBLEM ANALYSIS

The development of a highly mobile, relatively inexpensive system for detecting deviations from Kevlar helmet fabrication specifications involves consideration of both fundamental technical issues (basic principles) and practical operational issues. This section summarizes the major items of concern to this project, and the considerations taken for final selection of a laboratory system to be used in assessing overall performance characteristics.

DEFINITION OF ACCEPTANCE CRITERIA

Early discussions with Army and fabricator representatives resulted in the following acceptance criteria to be used throughout this study. These criteria have been derived from technical specifications mandating the manner in which Kevlar helmets are to be constructed and from the general expectations of the personnel involved with the process.

TABLE 1. General Acceptance Criteria

Sensitivity	Capable of detecting single missing layer in standard helmet (19 layers) Ref: MIL-H-44099A, 22 Dec 86, 3.4.1.1.2.
Resolution	Capable of detecting gap in two parallel layers separated by 3/32", Ref: MIL-H-44099A, 3.4.1.1.1, and discussion with the Technical Manager (TM) of this SBIR Project at Natick RD&E, Ms. Jane Astle.
Helmet thickness	0.350 inches, ± 0.010 inches when averaged over five measurements.
Time of inspection	Complete single inspection point in less than 15 sec. Ref: Technical Discussion with the TM. Complete inspection of entire helmet in less than ______ min. (to be determined). Ref: Discussion with the TM.
Sampling protocol	Helmet thicknesses for entire helmet in accordance with sampling plan (to be determined).
Cost of inspection	Undefined, but should be minimal.

Several typical operating conditions that dictate inspection procedure protocols were considered, including the times when inspections can be made using the final system. These conditions included, but were not limited to:

1. Ratio of relative amounts of resin to be found in comparison to the amount of cloth present in each area of interest. This is sometimes variable because of the use of resin to smooth over surface-layer gaps and pits.

2. Whether helmets were painted with opaque coatings or not.

3. Whether the inspection system can be calibrated for the ranges of materials which manufacturers are typically using in the fabrication of the helmets.

4. Whether the system can be calibrated for differences in processing practices that may lead to variations in the actual thickness of the helmets (such as that caused by folds in the Kevlar layup), the degree of cure to be expected, relative humidity (moisture content), differences in layup patterns (cross layer versus pin-wheel), etc.

It is clear that many of the processing variables have the potential to cancel out the effects of reliable inspection practices. These variables may have to be controlled through restrictive quality control operating practices in order to ensure that the reliability of the radioisotope thickness gauging meets the needs of the US Army. An alternate consequence of large variations in useful signals in comparison with random processing deviations could be the selective use of the radioisotope gauging concept throughout the entire area of the helmet structures. Recognizing this fact, the technical evaluation was conducted with the aim of discovering the ranges of parameters that would be required to attain a satisfactory inspection practice.

THE TECHNICAL ISSUES

There are several technical issues of significance that form the cornerstone of this technical evaluation study. The first is the determination of the source most likely to have the sensitivity and dynamic range to yield useful results in measuring the number of layers within a Kevlar helmet, and to detect local inconsistencies in its composition (voids, separations, etc.). The issue of dynamic range is largely controlled by the type of detection system chosen for use in conjunction with the radiation source.

The second technical issue is the system response to relatively ideal conditions in Kevlar materials. The probability of successful detection of meaningful deviations in the construction of Kevlar helmets will be determined, and to the extent possible, quantified.

Lastly, the operational problems to be found when working with actual helmet constructions will need to be identified and quantified, if possible. Theoretical expectations need to be verified through the use of typical helmet configurations.

SELECTION OF RADIATION SOURCES

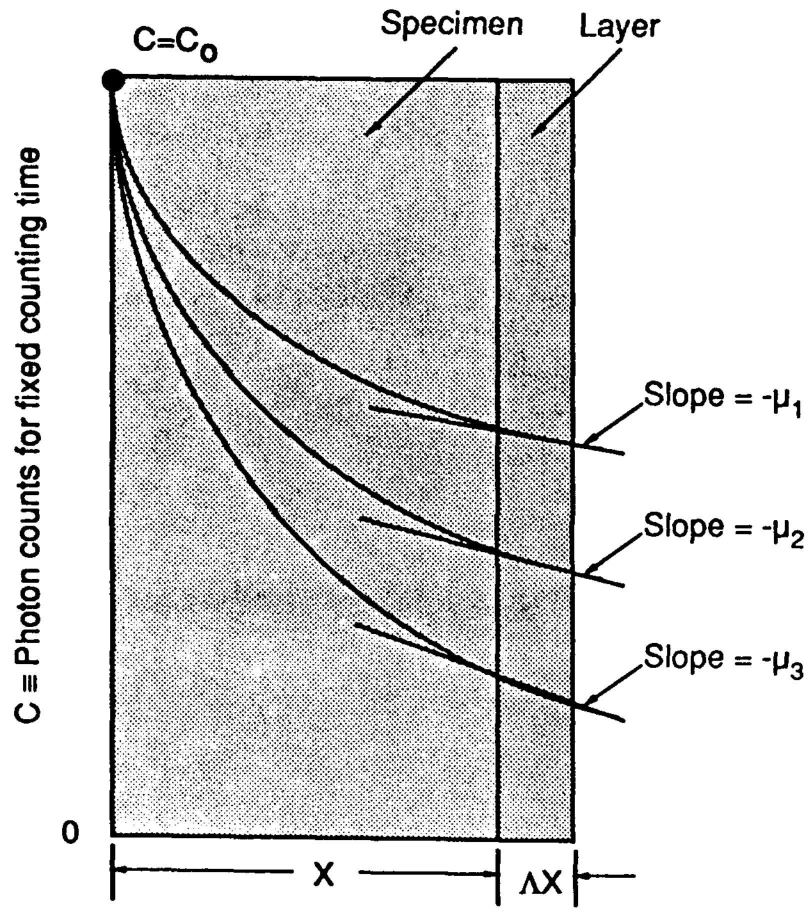
On the assumption (as verified by the tests cited in this report) that the energy transmitted through the kevlar composite follows the exponential decay law for radiation attenuation, the sensitivity to changes in thickness, x, decreases exponentially with increasing material (Kevlar) thickness. If sensitivity to changes in layer count is permitted to drop to one-half of that exhibited at the radiation entry surface, the product of the attenuation coefficient and of the thickness must be less than 0.7. For a helmet thickness of 0.350 inches, the resulting relative attenuation coefficient would be 1.9-inches^{-1} or 4.8 cm^{-1}.

For radiation attenuation rates much less than this, a small change in transmission and a corresponding lack of differential sensitivity is to be expected. This lack of differential thickness sensitivity will occur if sources with x-ray photon energies much higher than 20 keV are used.

For radiation attenuation coefficients much larger than 1.9, a smaller, usable amount of penetrating radiation will be detectable at the exit side of the Kevlar. In order to obtain measurable results under this circumstance, longer and longer averaging (exposure) times are required for a statistically valid sample of the actual radiation that can be transmitted through the test piece. As the effective attenuation coefficient becomes excessively large, even long wait times will not allow for an accurate assessment of the transmission of radioisotopic energy through the test piece.

Therefore, a compromise must be reached in the design of an inspection system that strikes a balance between the need for recording intense signals at the location of the detector, while at the same time exhibiting a large drop in transmitted intensity due to the presence of the intervening composite materials.

Since the uncertainty of the detected signal is dependent upon the Gaussian distribution of the radiation pulses reaching the detector, the sampling rate calls for a long dwell time during which the transmitted pulses can be "gathered." For a strong incident radiation beam, a statistically valid sample can be gathered in a relatively short time. For a weak incident beam, the sample time must be extended for a reasonable degree of significance to be ascribed to the test. Figure 1 depicts the dropoff in radiation intensity as a function of changes in the attenuation coefficient. It also addresses the loss of statistical validity of the layer count measurements brought about by this dropoff in radiation intensity.



- $C = C_0 e^{-\mu_i X}$ (i = 1, 2, 3, ...)
- $\mu_3 > \mu_2 > \mu_1$ in drawing.
- Layer sensitivity increases with increasing μ.
- μ increases with decreasing x-ray photon energy (E);
- Thus, sensitivity increases with decreasing E.
- But decreasing E decreases C;
- This increases the statistical uncertainty of C as E decreases:
- This increasing uncertainty in C with decreasing E causes the effective layer sensitivity to decrease with decreasing E.
- Thus, the net sensitivity reaches a maximum at one value of E.

Figure 1. Optimizing the sensitivity of a radiometric measure layer counting system through proper selection of X-ray source energy.

Initial surveys of available sources with characteristic radiation energies in the 15-to-25-keV range resulted in only a few available isotopes. X-ray tubes certainly can be operated in the low range, but are relatively expensive and do not satisfy the original request for a hand-held (and radiologically safe) inspection device. Table 2 summarizes the radioisotopes considered as part of this study.

TABLE 2. Radioisotope Characteristics

Radiation Source	Dominant Photon Energy (keV)	Operational Issues
X-ray Tube	Variable	Highly flexible but expensive, and exposure issues may be difficult to overcome.
Americium-241	14-18[a]	Low cost with long half-life but the presence of a strong line at 59.5 keV requires complex signal processing electronics.
Cadmium-109	22-26	Low attenuation coefficient precludes this isotope from yielding sufficient thickness sensitivity.
Curium-244[b]	14-18	Shows absence of high energy line structure; thus simplifies the adjunct electronics used in the detection of pulses.
Iron-55	6	Most attenuative in Kevlar but would require an unacceptably large source in order to yield statistically valid output.
Plutonium-238	14-18	Air shipment prohibited due to NRC regulations.

a. Considering only the portion of electromagnetic spectrum useful to the helmet inspection project.

b. Chosen for use in experimental studies at R&A.

As noted in Table 2, the isotopes of interest had dominant photon energies between 6 keV (Fe-55) and 26 keV (Cd-244). At the low end of the spectrum, the great rate of attenuation suggests a source which is highly sensitive to changes in thickness and material composition. However, if the limits of the detection system are exceeded, then such materials are useless for the current application. In the case of Fe-55, the introduction of a single layer of prepreg between the radiation source and the detector reduced the transmitted signal by 50 percent. When a 19-layer layup was used, it was impossible to detect the extremely low resulting transmitted energy.

Cadmium-109, on the other hand, has dominant photon energies of 22-to-26-keV. At these energies, 19 layers of Kevlar are too transparent to the higher energy radiation to allow reliable detection of the absence of one layer. Although a great deal of energy is available to excite the detection system, very little contrast due to variations in thickness is available and, therefore, this source is not considered feasible.

Between these two energy extremes lie three candidate sources with essentially the same dominant photon energy level between 14 and 18 keV. However, other operational difficulties preclude the use of Pu-238 and Am-241. The Nuclear Regulatory Commission (NRC) has severe transportation restrictions on Plutonium shipments, and because the other two sources responded comparably to the Kevlar, Plutonium was eliminated from the list of candidate sources.

Americium-241 possesses a very intense emission line at 59 keV (very high penetration), which interferes with the lower 14-to-18-keV lines when broadband detection systems are used. Because such systems are more economical in direct application settings, Americium-241 was eliminated from the list of candidate sources.

The remaining source, Curium-244, was selected for further experimental work in this study. All technical results discussed in the remainder of this report were obtained using a specially procured Cm-244, 30-mcu (millicurie) source with a 0.165-inch-diameter beryllium window. The half-life of Cm-244 is 18 years.

SELECTION OF RADIATION DETECTORS AND OUTPUT MEASURING EQUIPMENT

The selection of available radiation detectors is relatively narrow in comparison with the number of radiation sources available. The primary candidates considered in this study included scintillation detectors, gas proportional (GP) counters and Geiger-Mueller (GM) tubes. The very rudimentary experimental work performed on Kevlar composites, prior to the submittal of this SBIR proposal in December, 1986, showed that an energy sensitive detector and a single or multichannel analyzer would probably be necessary to obtain a significantly high signal-to-noise ratio to adequately assess the sensitivity of the system during the Phase I work. Of the three detectors mentioned, only GP and scintillation detectors have energy resoluting capabilities. However, scintillation detectors are several orders of magnitude more sensitive than GP detectors, and consequently require shorter counting time to achieve adequate counting statistics. Also, the GP detectors are more ruggedly constructed, a definite advantage in the production environment, the end-use application.

Because the sodium iodide (NaI) variety of scintillation detector is the most sensitive type, is readily available at relatively low cost, and is designed for use at room temperature (some scintillators require liquid nitrogen cooling), it was selected for the laboratory (Phase I) system. The already available NaI detector had 1 1/2-inch x 1-inch crystal and a 0.040-inch thick aluminum window. The aluminum window has a tendency to moderately attenuate the lower energy components of the emission spectrum of Cm-244, and to center the peak at 18 keV rather than at 14-to-16-keV. A new NaI detector with a beryllium window that would not attenuate the low energy components of the spectrum could have been purchased and used in this work. However, the estimated improvement in system sensitivity was not enough to warrant taking this approach for Phase I.

DESCRIPTION OF LABORATORY SYSTEM

The laboratory system has three major elements: (1) the detector, source, and beam collimator, (2) a detector signal amplifier and multichannel analyzer (MCA), and (3) a computer-based data acquisition subsystem.

Figure 2 is a schematic drawing of the complete laboratory system. The system records the total number of x-ray photons (or counts) with energies over a specific range (window) produced by the Cm-244 source and detected by the NaI crystal mounted in the detector. The photon energies are distributed into discrete channels in the MCA. The resulting energy spectrum is displayed in real-time on the MCA scope.

At the end of a specified counting period, the total number of counts in the window is displayed digitally on the scope of the MCA. The fractional (percent) transmission of the helmet, or other test panel, is determined by dividing the total number of counts obtained with the helmet mounted in the x-ray beam by the total number of counts with helmet removed from the beam. The spectrum is stored digitally in a microcomputer that provides hard copies of the number of counts in each channel and copies of the energy spectrum.

Figure 3 shows an overall photographic view of the system currently in use. The components are arranged in the same order in this view as shown in the schematic drawing (Figure 2). The detector and test piece fixture appear on the far right, and the computer is on the left. Figure 4 shows a helmet under test, mounted in the simple ring stand test fixture used in an early version of the system.

The final version of the system has an improved test fixture that incorporates a compact source holder with an add-on beam collimator and a detector collimator. Figures 5 through 8 show the test fixture and its use in measuring the x-ray transmission of one of eight Kevlar helmets tested on the system. The two collimators are aligned axially by inserting a close, slip-fit steel rod through the collimator bores before the helmet is mounted.

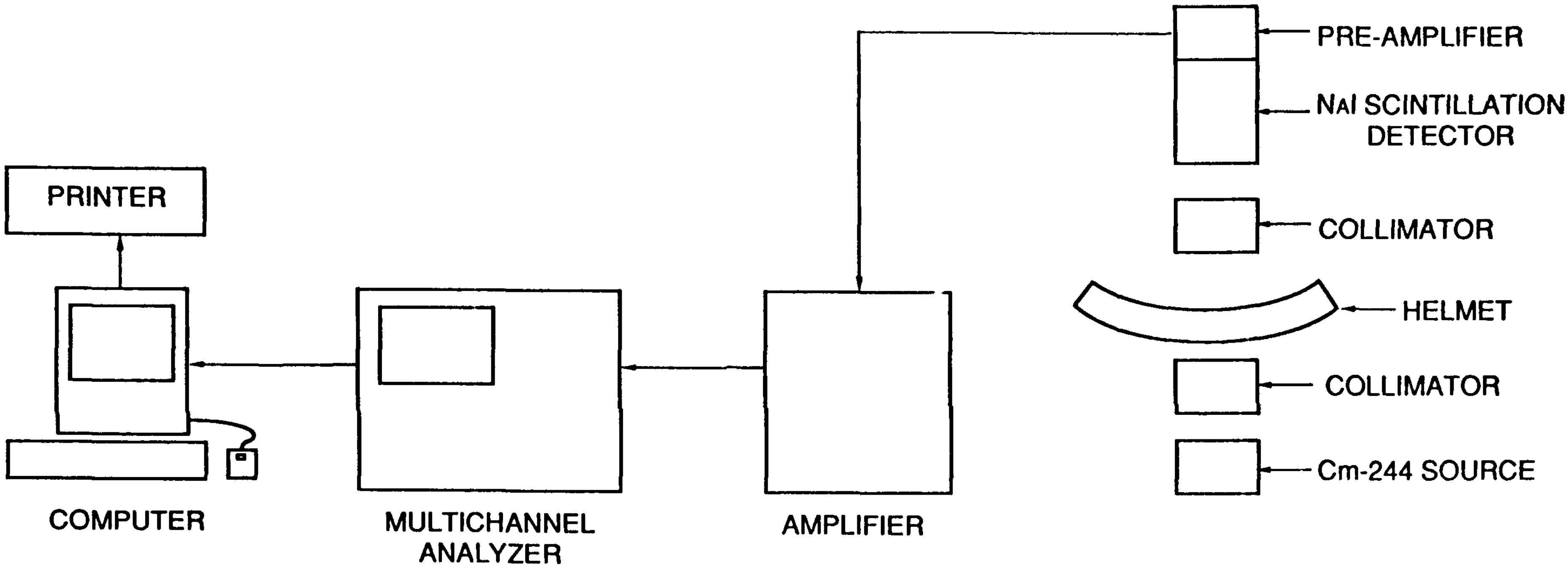


Figure 2. Schematic drawing of final laboratory system.

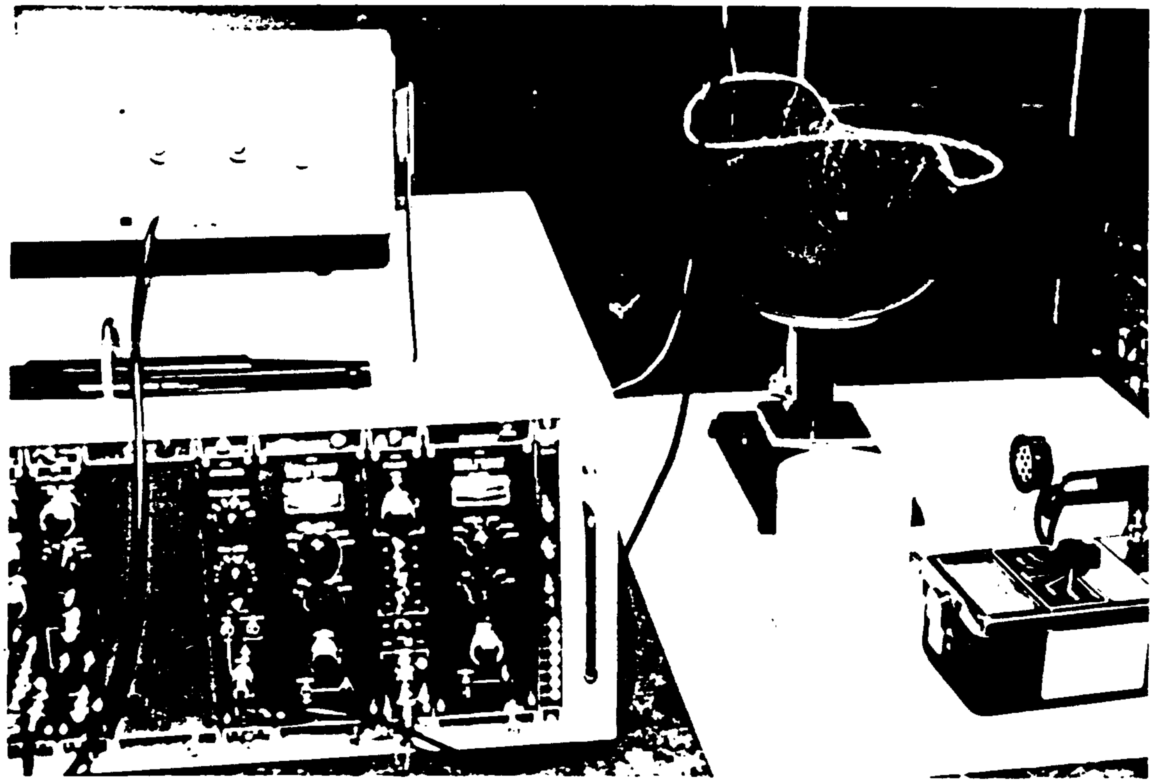


Figure 4. View of early version of system showing helmet on simple test stand.

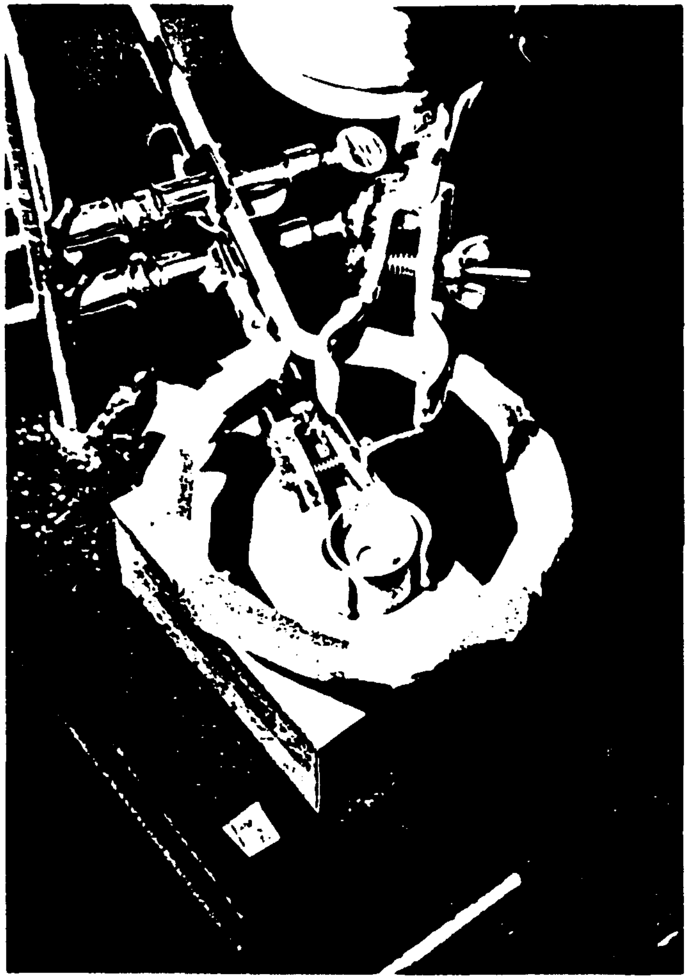


Figure 5. Source in housing in test stand.

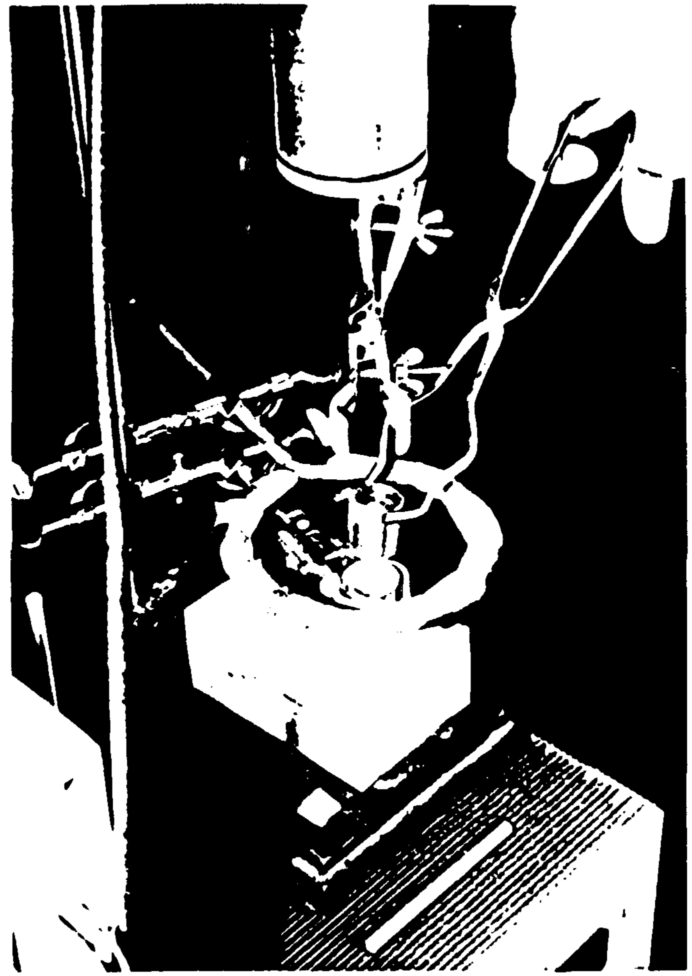


Figure 6. Insertion of detector collimator into source housing. Detector appears at top of photograph.

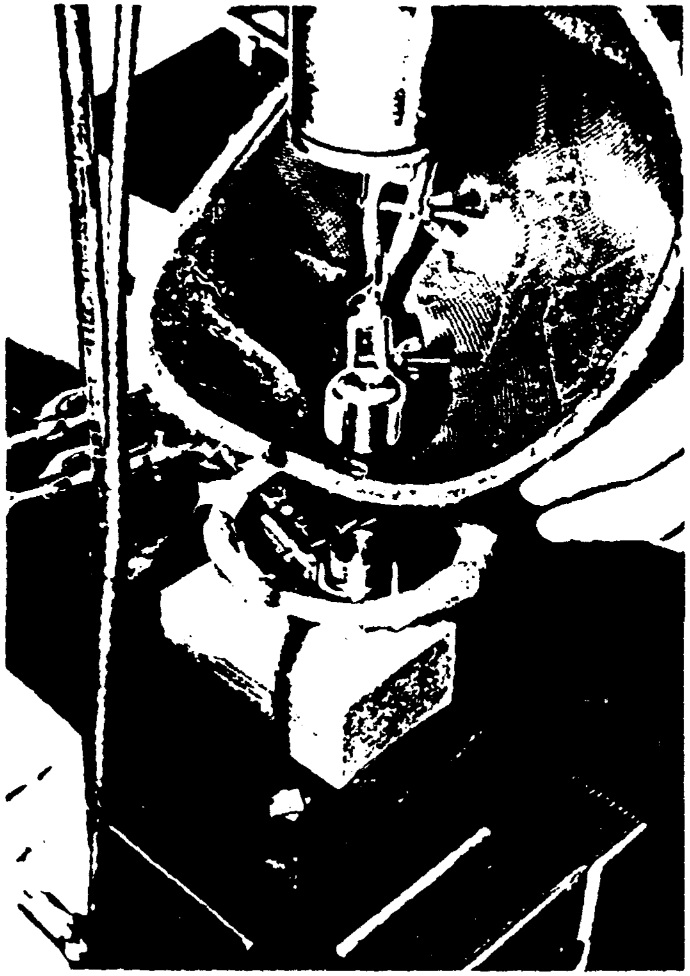


Figure 7. Mounting helmet between collimators in test fixture.

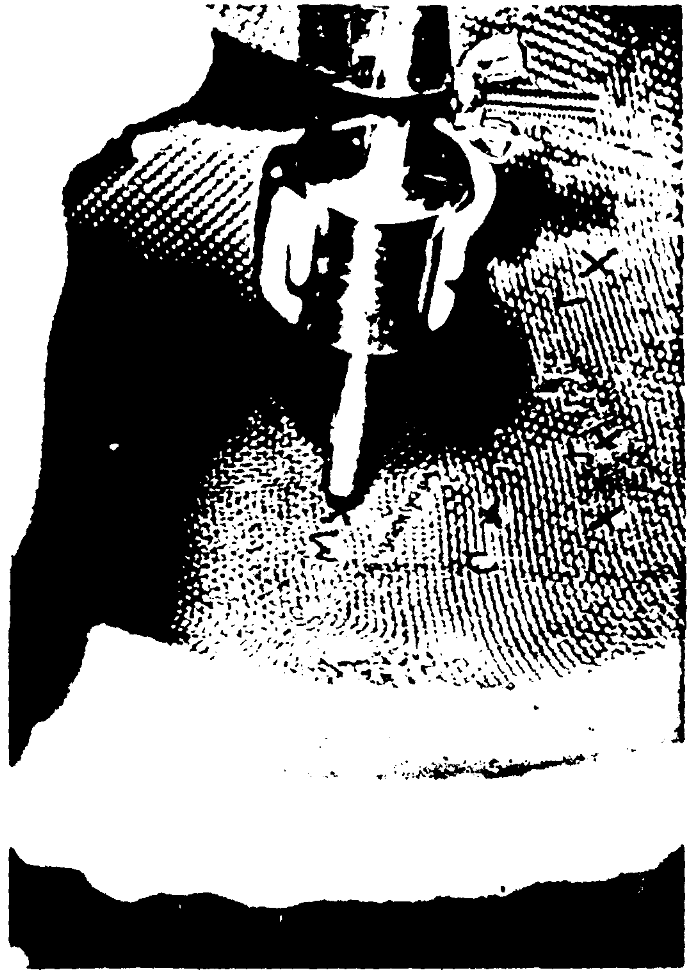


Figure 8. Mechanically locating beam target using alignment rod.

After the helmet is mounted on the ring support of the fixture, the center position of the beam is determined mechanically by inserting the rod through the bore of the upper collimator and allowing it to rest on the inner surface of the helmet. The contact point will be the location of the x-ray beam after the lead radiation shield (a small square, not shown) is removed from the top of the bottom collimator.

Six pairs of collimators with bore diameters ranging from 3/32-inch to 1/4-inch were machined from brass and used at various stages of radiometric testing of panels and helmets. The 1/4-inch collimators were used in all final tests on helmets and panels. These collimators provided enough beam intensity for adequate counting of statistics and allowed lateral gaps in layers as small as 3/32-inch to be detected.

Figure 9 is a photograph of the collimators with their matching alignment rods. Figure 10 is an engineering drawing of upper and lower collimators and the source holder. The lower collimator slips into, and rests in, the source holder.

Brass was selected as the collimator material because of its machinability. It also provides more than adequate shielding. With the collimators in place, the radiation level is less than 1 mr/hr at off-axis positions.

During testing, the energy window of the MCA is set so that counts are taken over the full width of the detected energy spectrum. A computer generated plot of the spectrum is shown in Figure 11. The spectrum peaks at about 17 keV, which corresponds to the location of the L characteristic emission line line produced by the source. During a typical test, the upper and lower energy bounds of the MCA counting window are set at the channels corresponding to 12 kev and 26 kev. The MCA then sums up all counts in that window and displays this number.

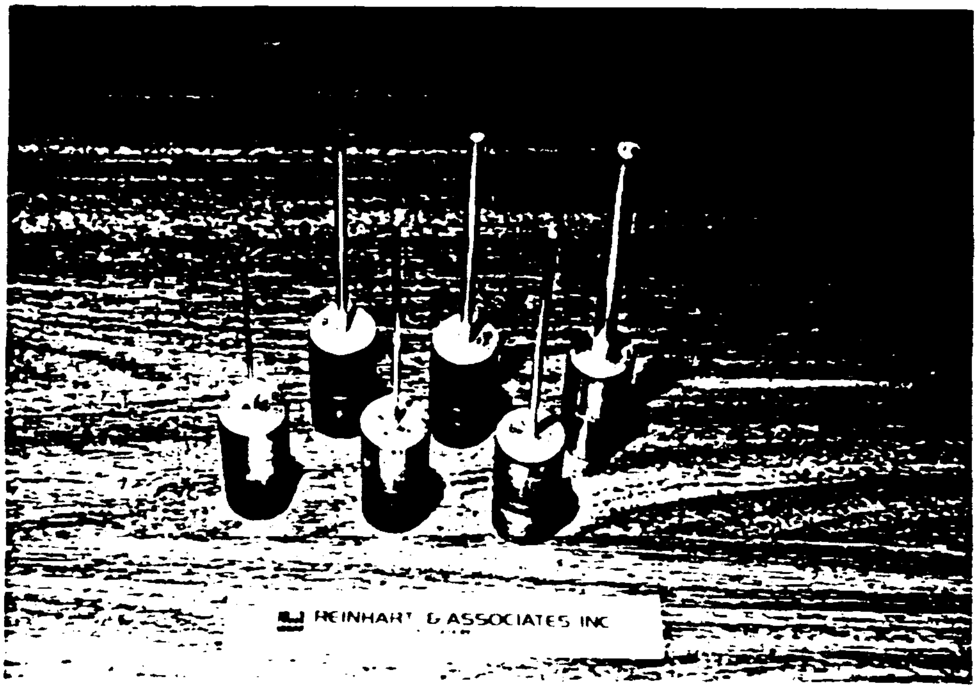
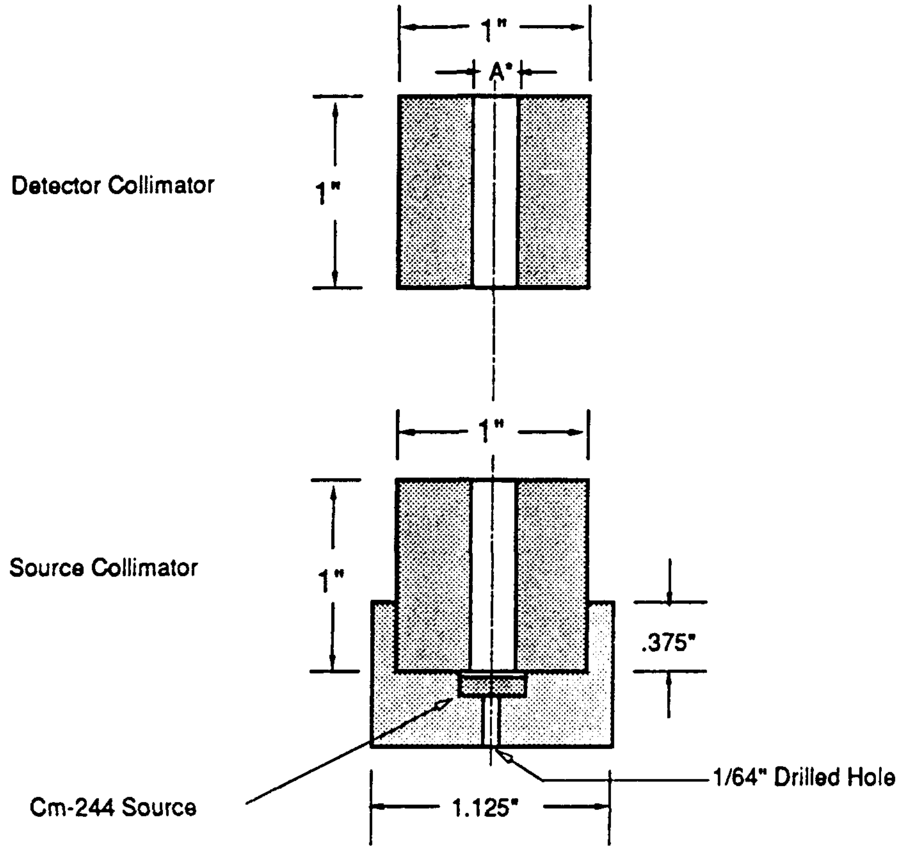


Figure 9. Six pairs of collimators with their aligning rods.



NOTES:A* = 3/16 or 1/4 inch, depending on application

Material:Brass

Figure 10. Engineering drawing of beam collimators and source.

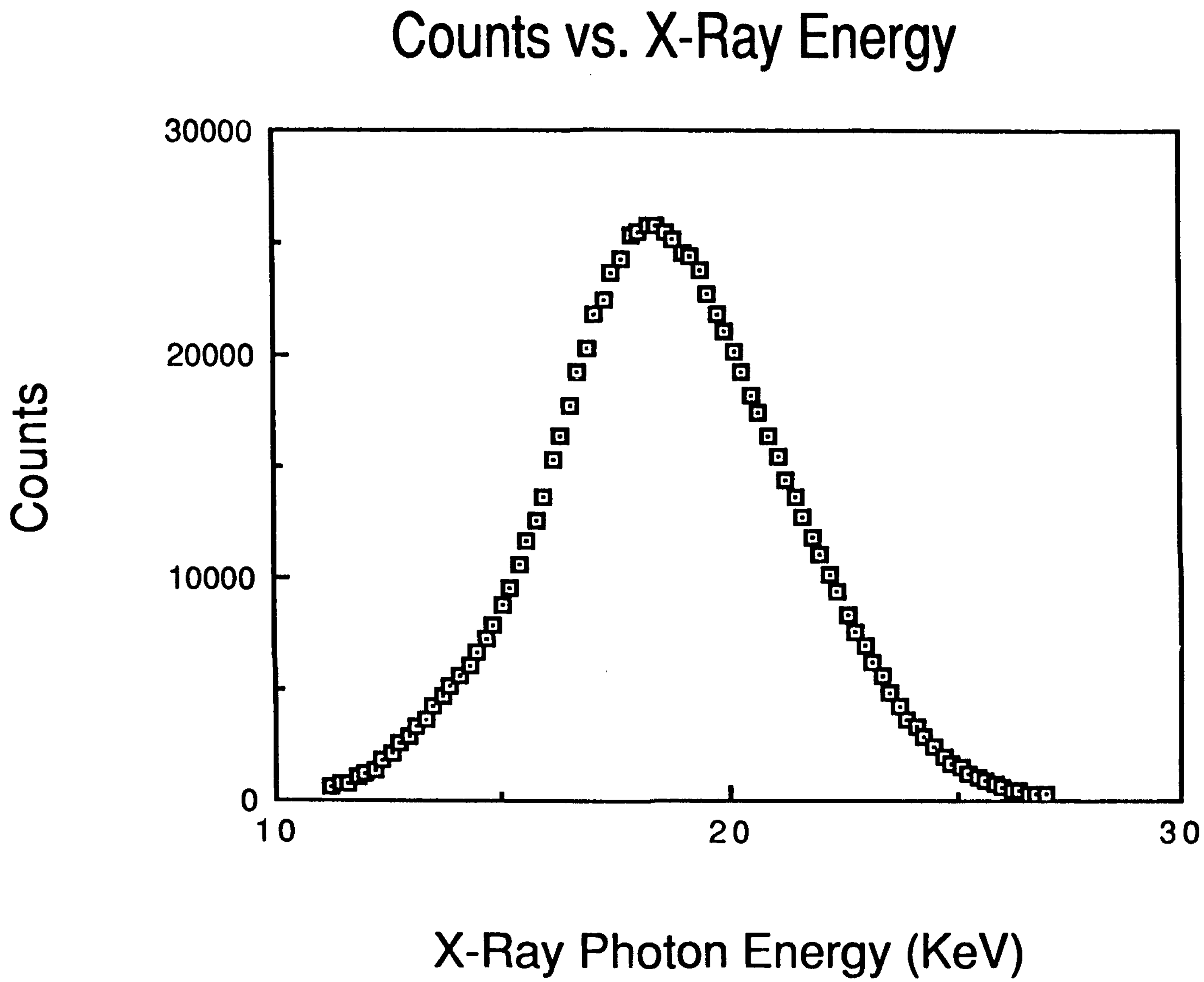


Figure 11. Graphical mode output of multichannel analyzer showing calibrated energy (KeV) spectrum of Cm-244 x-ray photons reaching the scintillation detector crystal.

TECHNICAL RESULTS

The technical results obtained during the course of this Phase I project fell into four general categories. These included: (1) preliminary experimental studies concerning the selection and applicabilities of available sources and detectors for use in the thickness gauging application for Kevlar, (2) performance tests of the final system on flat test specimens, (3) performance tests of this system on a specially fabricated helmet crown specimen containing 16 discrete regions of various lateral dimensions with 1 to 3 layers missing, and (4) performance tests on 8 production helmets having a wide range of localized surface blemishes. The results of tests conducted in category (1) are included in this section for purposes of record, and may appear to be out of order since the final system was described in the previous section. Task categories (1) through (4) were performed in numerical order.

APPLICABILITY OF AVAILABLE SOURCES AND DETECTORS

Experimental evaluations were conducted on each of the radioisotopes listed in Table 2. These evaluations were intended primarily to assess the potential of each of these sources to yield sufficient depth resolution to meet the deviation requirement of one layer in nineteen.

The tests were conducted on a set of 3-inch x 3-inch Kevlar composite panels fabricated by Devil's Lake Sioux (DLS). Panels containing 15, 16, 17, 18, and 19 layers were tested using the radioisotopes listed in Table 2. A sodium iodide detector was used in conjunction with the amplifier and MCA described earlier. The results of these preliminary tests are presented in Table 3.

TABLE 3. Source Sensitivity Evaluation

Source	Sensitivity	Operations Issues
Am-241	—	Only available source had a stainless steel window which completely shielded low energy photons.
Cd-109	2-3 layer	Barely discernible distinction between single-layer change.
Cm-244	< 1/2 layer	Clearly discernible distinction for a single-layer thickness change.
Fe-55	<< layer	Single layer (alone) dropped detected signal to one half. At 19 layers, no transmitted signal could be detected.
Pu-238	< 1/2 layer	Clearly discernible distinction for a single-layer thickness change.

On the basis of these results and the information that Pu-238 is not readily transportable due to stringent NRC rules on this radioisotope, Cm-244 was selected for use in the final radiometric testing system.

RECORD TESTS ON FLAT PANELS

The purpose of conducting the tests reported in this subsection was to carefully evaluate the sensitivity of the final laboratory system to changes in 1 thickness layer out of 16 to 20 layers. Flat panels were used at this stage of the project to assure that the test pieces would have maximum uniformity and that geometry would not influence the outcome of the tests.

In addition to assessing the sensitivity of the system to the number of Kevlar layers, other issues were addressed. These issues included: (1) lateral resolution of the system and its ability to detect narrow lateral gaps, (2) the effect of in-flow of resin into a gap on the detectability of a gap only 3/32-inch wide and one layer deep, and (3) the effects on layer sensitivity of resin-rich and resin-poor conditions and variations of the thickness of paint on production helmets.

The test pieces used in these tests were made from a single 6-inch x 6-inch x 16-layer Kevlar composite panel obtained from Unicore Prison Industries (UPI). A 1-inch square coupon was cut from the panel and soaked overnight to soften the resin enough to allow careful separation of the square into 16 separate layers. These layers were allowed to dry thoroughly. The x-ray transmission of the 16-layer stack of test coupons was measured using the laboratory system and compared with the transmission of the intact 16-layer panel. The difference between the two attenuation values was found to be less than the system sensitivity under ideal conditions, or 0.3 percent. The panel and stack of coupons are shown in Figure 12.

In the first set of tests, the relationship between x-ray transmission and the total number of layers was determined experimentally. The first radiometric measurement was performed on the basic 16-layer panel. Then the number of layers was increased, adding squares of the cured composite one at a time. The data recorded was the total number of counts under open tube (no panel) and panel-in-place conditions.

The test results are shown in Figure 13, which is a semi-log plot of relative counts (fractional transmission) versus the total number of layers. The data points fit on a straight line that passes through 1 on the log scale, which demonstrates the exponential relationship between fractional transmission and the total number of layers in a Kevlar composite panel. The attenuation coefficient equals 0.0695 per Kevlar layer. A change of effective panel thickness of one layer produced approximately a 2 percent change in the relative transmission (or attenuation) of the beam. Standard pulse counting statistics showed uncertainty in the number of counts to be less than 0.6 percent at a 99.95-percent confidence level. Thus, the system should be sensitive to changes as small as 1/2 layer if the effects of variabilities in the resin/fiber quantity ratio do not impair the sensitivity of the radiometric measuring technique.

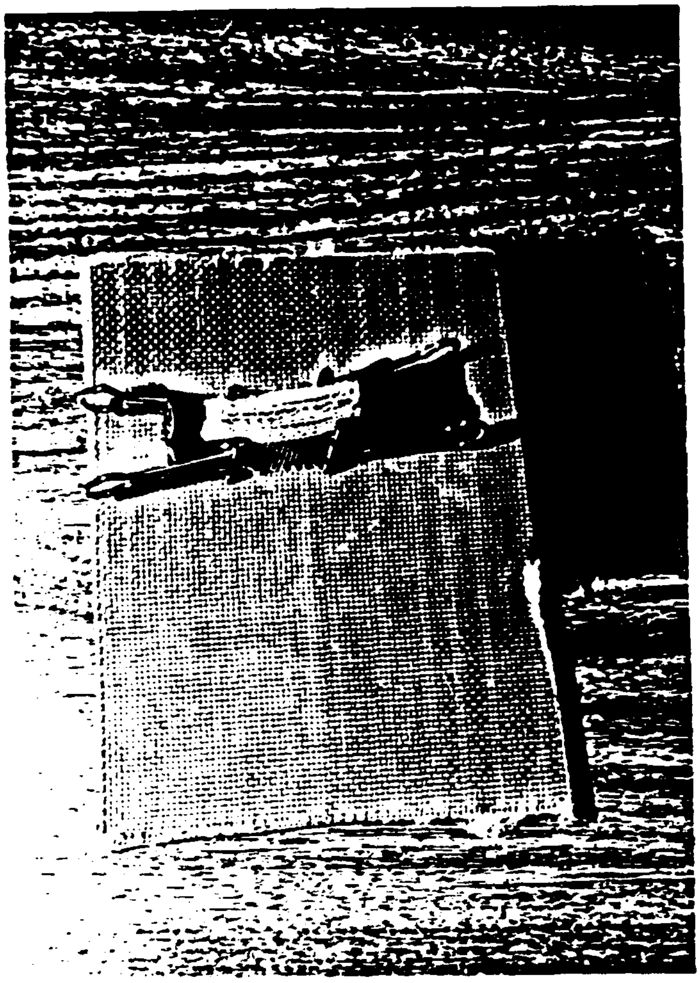


Figure 12. Flat Kevlar composite test panel and stack of 1-layer cured kevlar composite squares.

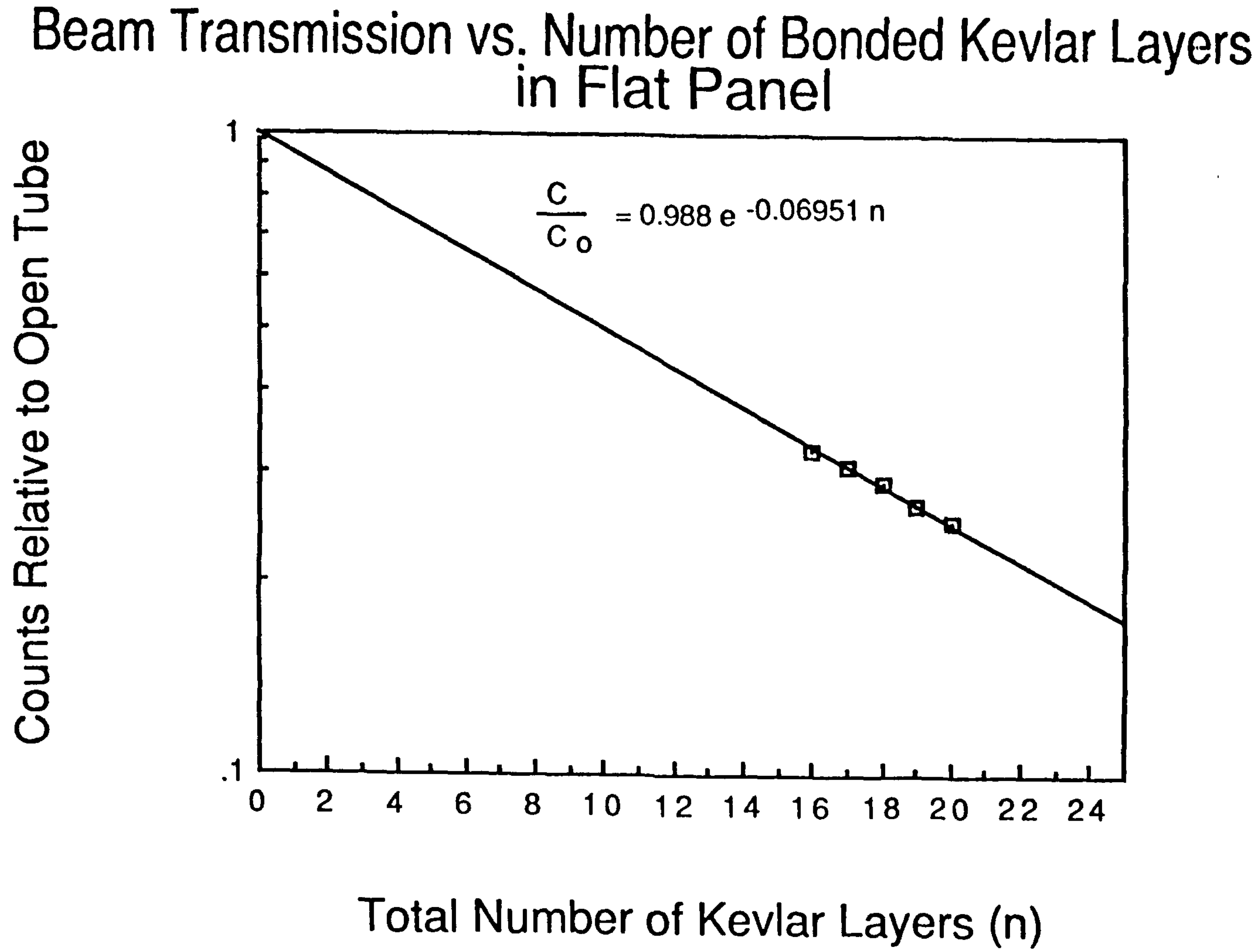


Figure 13. Variation of x-ray photon transmission with total number of Kevlar layers in test panel.

The effect of adding constant thicknesses of various helmet fabrication materials was also investigated experimentally. Known thicknesses of spray paint, cured helmet resin, Kevlar prepreg, and virgin Kevlar cloth were added to the basic 16-layer panel and the change in count rates was measured. The transmission data was then normalized to data for an 18-layer specimen. Figure 14 is a semi-log presentation of the test results. The negatives of the slopes of the trend lines are the transmission coefficients of the added materials. This figure shows qualitatively that the transmission of low energy x-rays is fairly insensitive to the amount of pure (no resin) Kevlar cloth in a panel, but very sensitive to thin layers of paint or resin.

The results of this test are summarized in Table 4. Notice that only approximately 7 mils increase in the thickness of surface paint on a helmet, or in the total effective thickness resin over the entire thickness of a helmet, will mask the absence of 1 cured layer of composite. Notice also that resin and spray paint are at least 7 times more effective than the virgin Kevlar cloth in attenuating low energy x-rays.

The ability of the system to detect a lateral gap of 3/32-inch width and one layer depth was investigated. A gap having these dimensions was simulated by clamping two cured Kevlar coupons 1/32-inch apart onto the 16-layer panel. Radiometric measurements were taken for the open tube condition and then over the gap and over the 17-layer region. The beam and detector collimators had 1/4-inch-diameter bores. A difference of 0.02 (2%) in the x-ray transmission at 16- and 17-layer sampling positions was obtained, which combined with the previous results shows that a one-layer change was detected. This result is shown in Figure 15.

The effect of resin flowing into the gap on the radiometric measurements was investigated. Resin flow was simulated by adding thin, 3/32-inch-wide strips of cured resin to the gap. Figure 15 shows that when only 5 mils of resin was in the gap, the x-ray transmission through the panel at the gap was the same as the value measured for x-rays passing through the 17-layer portion of the panel. Therefore, only 5 mils of resin in the gap destroyed the ability of the system to detect the gap.

TESTS ON CURVED CROWN SAMPLE

A 19-layer helmet crown region test sample was fabricated for these tests by Unicore (UPI). The sample was rectangular and was approximately 4-inches long and 6-inches wide. It contained rectangular flow regions having 1, 2, and 3-layer cutouts of Kevlar cloth. Each region was 1-inch long. The widths of the regions varied from 1/8-inch to 1-inch. Figure 16 is a photograph of the sample. The defect areas are labelled left to right from 1 to 16.

Figure 17 is a radiograph of the sample shot at 25-keV tube voltage on fine grain, single emulsion x-ray film mounted in Ready Packs. The dark and light areas of the radiograph correspond to low attenuation and high attenuation areas, respectively. Notice that wider flaw regions tend to be less attenuative to x-rays than are the narrower regions. These narrower regions are considerably more attenuative to x-rays than the surrounding 19-layer material, suggesting flow of resin into the flaw areas from surrounding material.

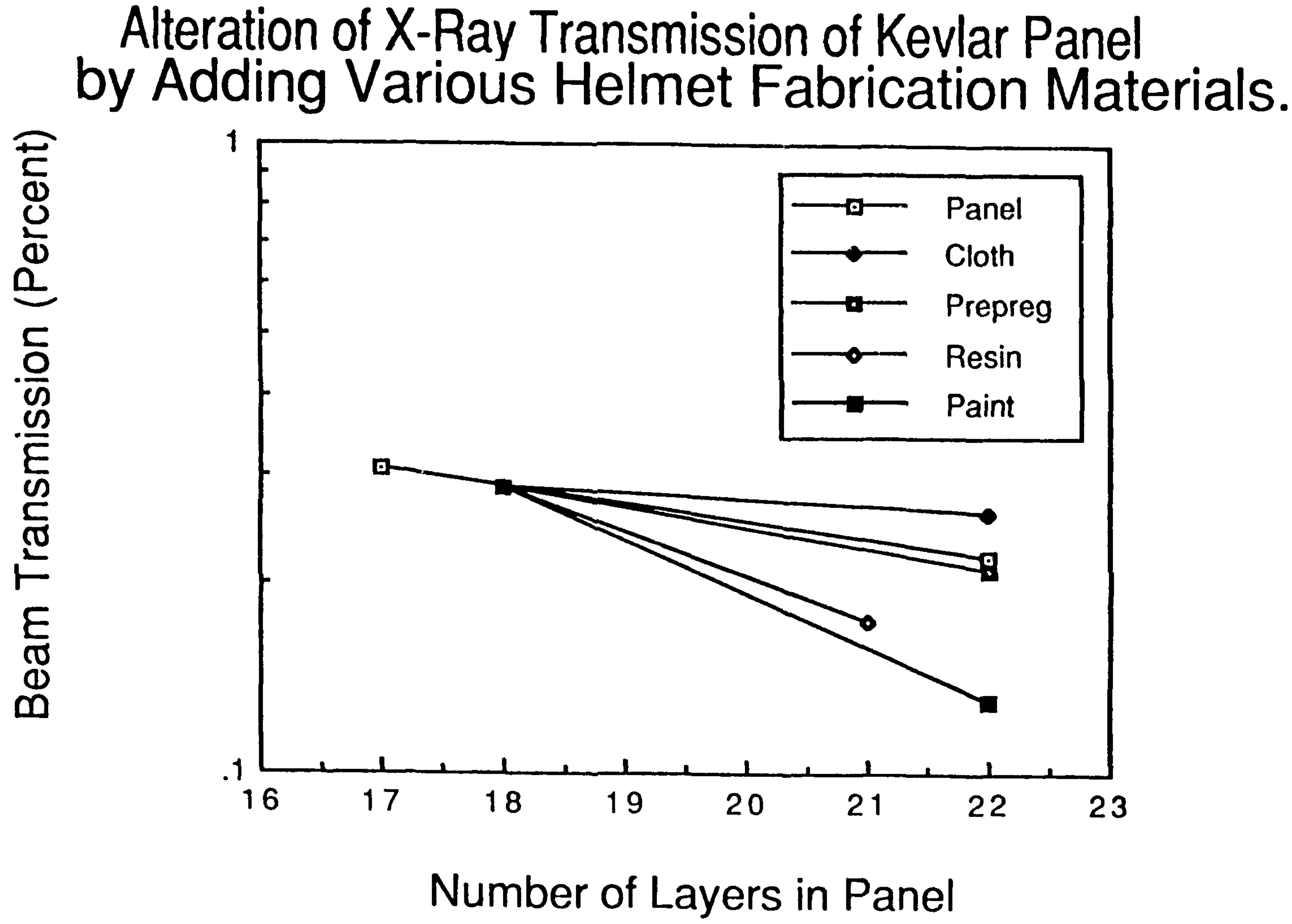


Figure 14. <u>Effect on x-ray transmission of adding the same thickness of various materials to Kevlar composite</u>.

Table 4. Relative Attenuation of X-rays by Various Helmet Fabrication Materials

Material	Attenuation coefficient, μ (in units of percent: layer of bonded Kevlar composite)	Radiometric equivalent to 1-layer bonded Kevlar	Relative effectiveness of equal thickness of material in attenuating beam
Spray Paint	0.194	6.6 mils	8.5
Resin	0.169	7.5 mils	7.0
Bonded Kevlar	0.0695	–	3.0
Prepreg	0.071	0.97 layer	3.1
Kevlar Cloth	0.0228	3.0 layers	1.0

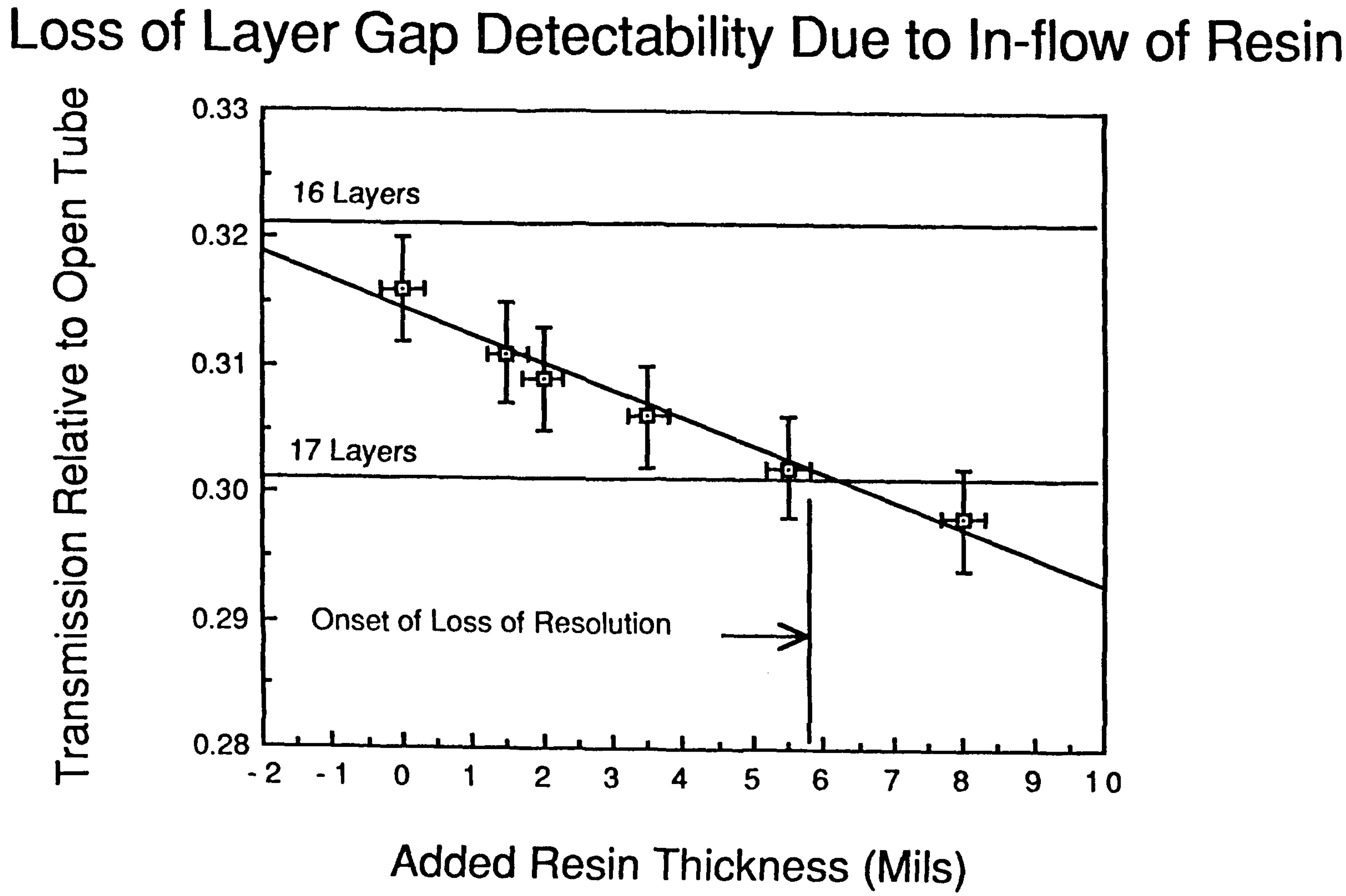


Figure 15. Loss of detectability of 3/32 inch wide, one-layer deep gap in layers due to in-flow of resin.

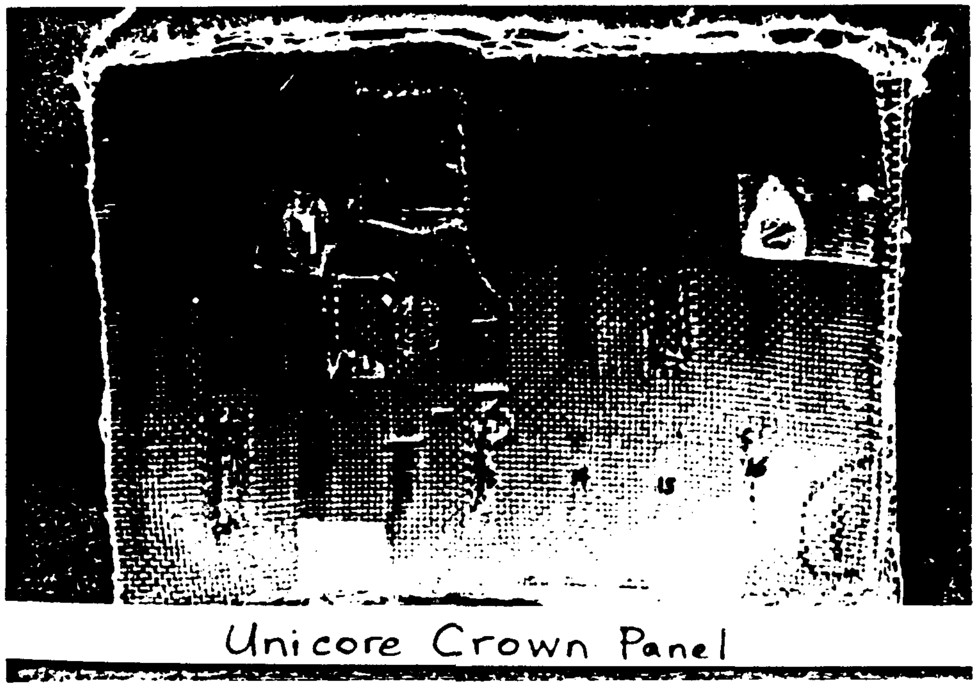


Figure 16. Photograph of Unicore helmet crown test panel.

Figure 17. Photographic print of radiograph of Unicore crown panel.

The unflawed regions of the crown and the centers of each flawed region were tested on the radiometric system. Collimators having 1/4-inch-diameter bores were used. The test results are shown in Figure 18. The numbers of the sampling locations increase as the widths of the flaws become smaller. The numbers at the data points correspond to the numbers of missing layers at the sampling location. Notice that at sampling locations 1 through 5, the measured attenuation of the beam was less than the attenuation of the unflawed 19-layer material. At sampling (flawed) locations 6 through 16, the attenuation was higher than through the 19-layer material. This result suggests flow of resin into the flawed (cutout) areas had occurred.

Figure 19 shows a comparison of the measured attenuations at the sampling points with the values of the attenuation that would have been measured if excess resin had not flowed into the cutout (flawed) areas. The theoretically derived attenuation values were obtained by subtracting 2 percent times the number of layers missing at each sampling location from the attenuations of the 19-layer (unflawed) material. There is as much as a 9 percent difference between the measured and computed attenuations and the measured values are always larger than the computed values of attenuation. Therefore, in the worst cases, the crown panel appears radiometrically to be 4-1/2 composite layers too thick. Using Table 4, we can calculate that 4-1/2 layers is equivalent to 34 mils excess resin. However, this resin excess could have been (and probably was) distributed over the entire thickness of the crown panel at the sampling locations.

To evaluate this hypothesis and confirm the number of layers missing in each region, the crown sample was destructively examined. The panel was cut up in such a way as to leave half of each sample area intact to allow for retesting. Figure 20 shows the crown cut up into curved sections.

Two sections containing representative regions of each sampling area were soaked overnight in methylene chloride and then stripped apart layer by layer to show the layer cutouts and to reveal resin build up areas. Figure 21 is a photograph of a section of one layer obtained in this way.

The correct number of cutouts was found at each sampling position. Some localized buildup of resin was found on the solid layers below (or above) the cutouts. Even very rough measurements of the localized excess resin thicknesses proved to be statistically invalid. It is believed that the bulk of the excess region in each area was distributed over the thickness of the sample.

TESTS ON HELMETS

Eight helmets, containing localized surface blemishes that made them unacceptable as deliverable production units, were obtained from three manufacturers. Used in the radiometric system tests were:

- 3 helmets from Devil's Lake Sioux (DLS),
- 4 helmets from Unicore Prison Industries (UPI), and
- 1 helmet from Geonautical (GEO).

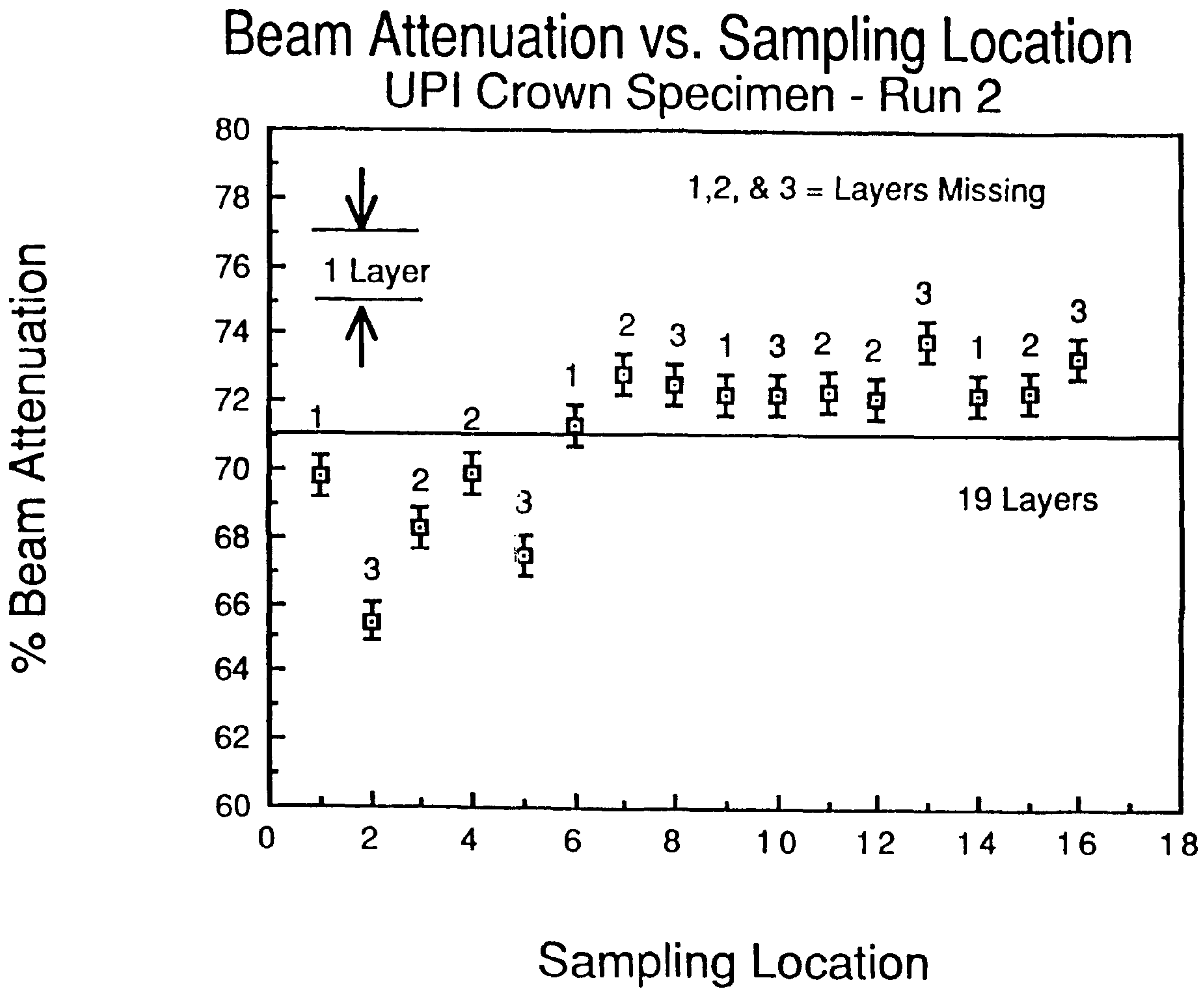


Figure 18. Variation of x-ray beam attenuation by sections with missing layers in crown specimen.

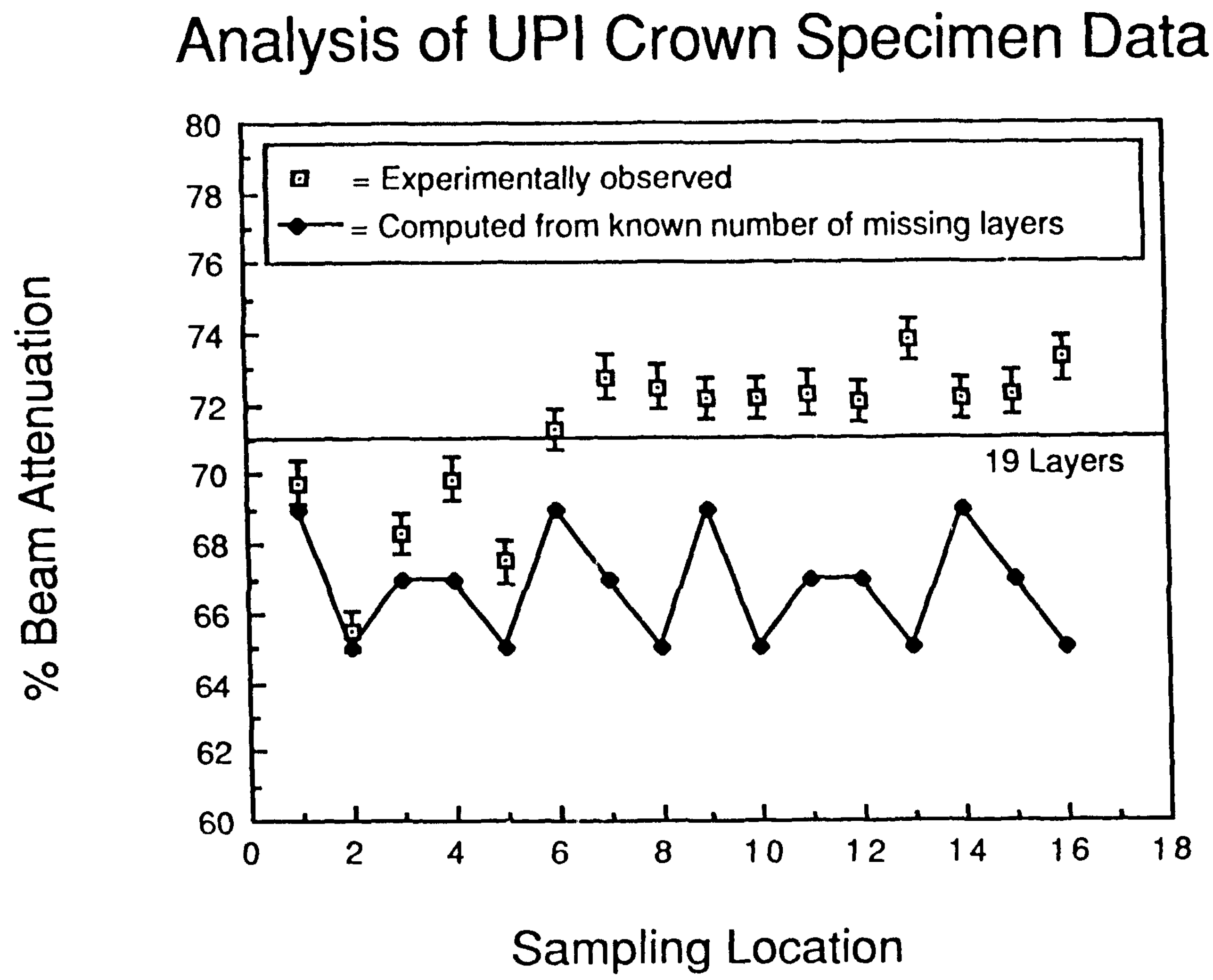


Figure 19. <u>Comparison of attenuation data for crown specimen with 19 layer data theoretically corrected for missing layers</u>.

Figure 20. Crown specimen cut into strips before chemical softening of resin.

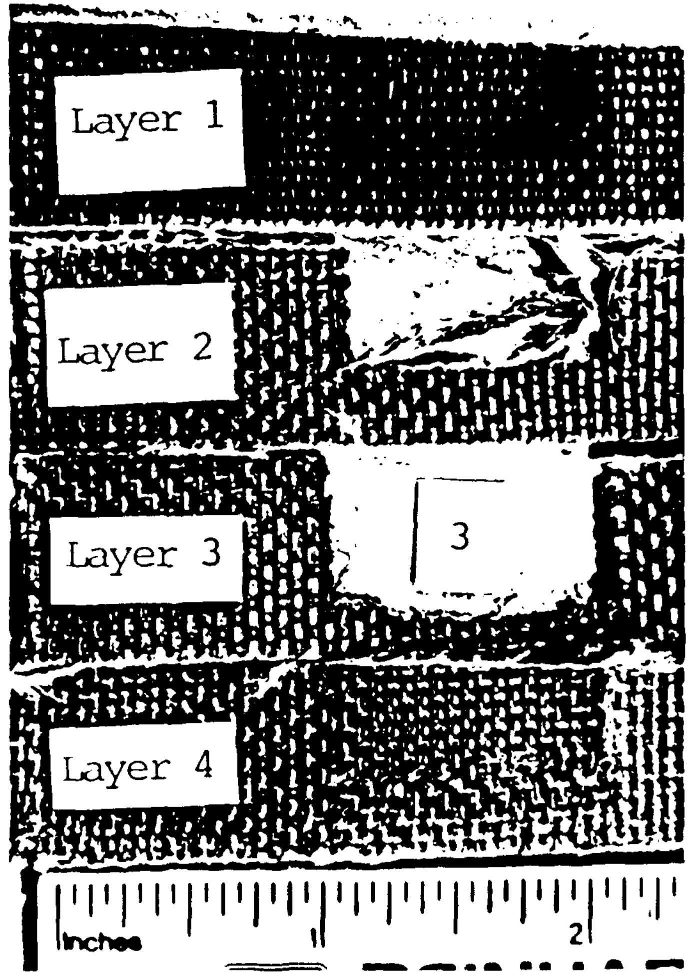


Figure 21. Macrophotograph of separated layers showing regions with missing Kevlar cloth and resin build-ups.

The collection of helmets used in the tests is shown in Figure 22. Figure 23 is a view of helmet DLS-6. The narrow white strips of tape mark off various sections of this helmet that were examined radiographically.

Twenty numbered reference positions were marked off on the interior surface of each helmet using permanent ink pen. Ten of these positions were located in the crown areas, which have no layer overlap regions. The remaining ten positions were located in the skirt area but within a few inches of the boundary of the crown. There were overlap regions at these positions in the skirt area. All helmets were then radiographed.

Figures 24 and 25 are the photograph and the radiograph of the numbered reference area of helmet DLS-6. Notice the generally good agreement between the surface appearance of the helmet and the x-ray image of the helmet. This agreement suggests that the results of visual inspections might have some correlation with radiographic and radiometric evaluations of helmets. The possibility of such correlations is evaluated later in this section of this report.

The crown and skirt regions of each helmet were tested using the radiometric system. Figure 26 shows the test results for helmet DLS-6. Notice that the attenuation is constant to within experimental error (depicted by error bars) throughout the crown region, but varies by amounts that correspond to nominally one-half-to-one-layer thickness in the skirt area of the helmet. The scatter in attenuation values might be due to layer overlaps, variations in the resin thickness distribution, gaps in layers, or any combination of these factors.

The radiometric test results for all helmets are summarized in Table 5 which shows arithmetic means of the transmission value in percentages and the standard deviation of these transmission values. Notice that the averaging process smooths out the data considerably, and that the means for crown and skirt regions have standard deviations equivalent to a variation of considerably less than one layer of composite. This observation suggests that if enough sampling points were used on each helmet, the average attenuation value would be a reasonably good indication of the absence of large sections of missing composite layers.

It was noted in this section and a previous section of this report that x-ray transmission of Kevlar composite is extremely sensitive to variation in the resin/fiber ratio, and that the visual appearance of a helmet's exterior surfaces seems to mirror the bulk morphology of the composite within the helmet. Both observations suggest that the degree of localized darkening (or lightening) of the surface of a helmet might correlate with the radiometrically-measured transmission (or attenuation) values in these localized regions. A test was conducted to assess this possibility.

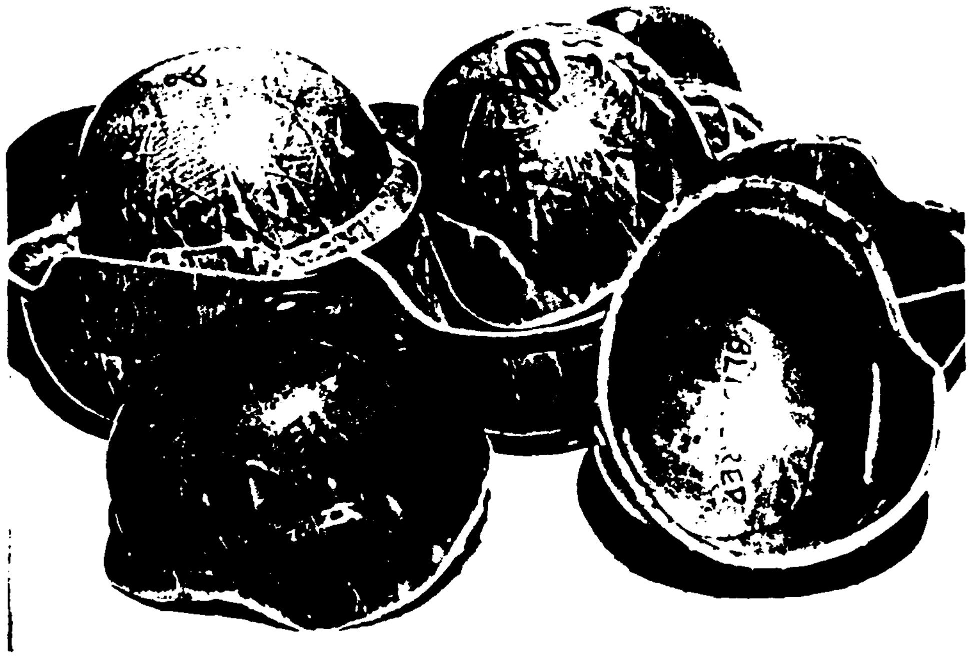


Figure 22. Overall view of the collection of helmets tested by radiometry.

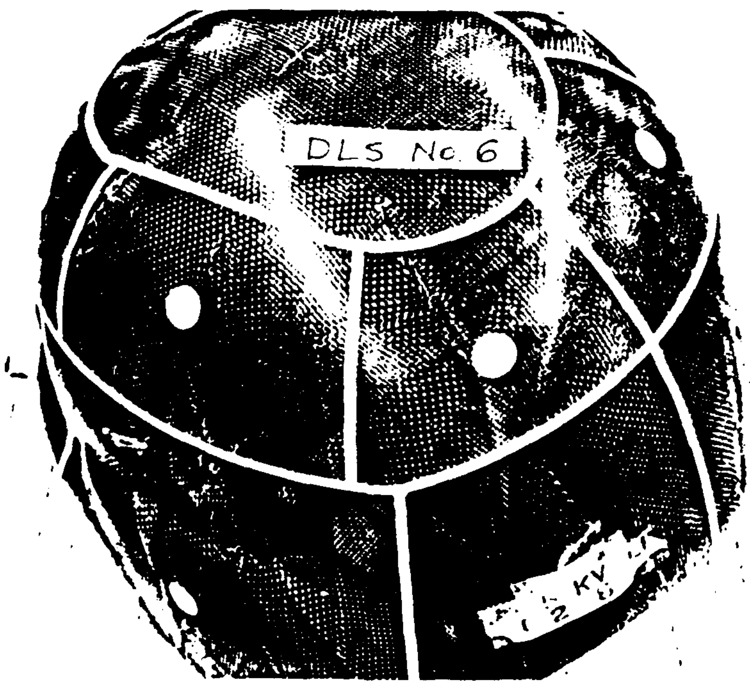


Figure 23. Close-up view of helmet DLS-6.

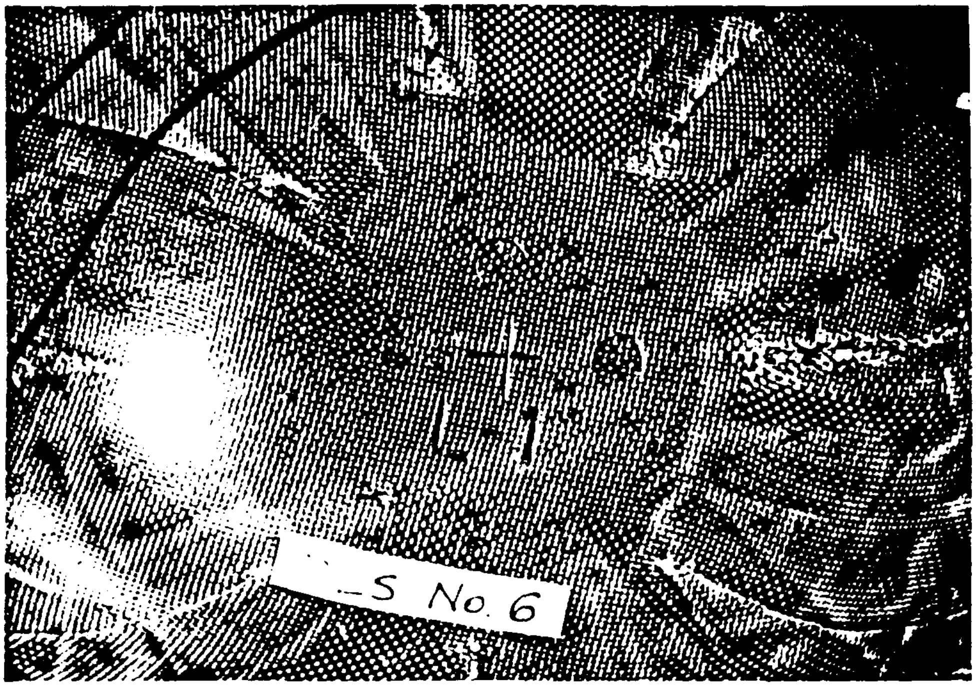


Figure 24. Photographic view of interior surface of helmet DLS-6.

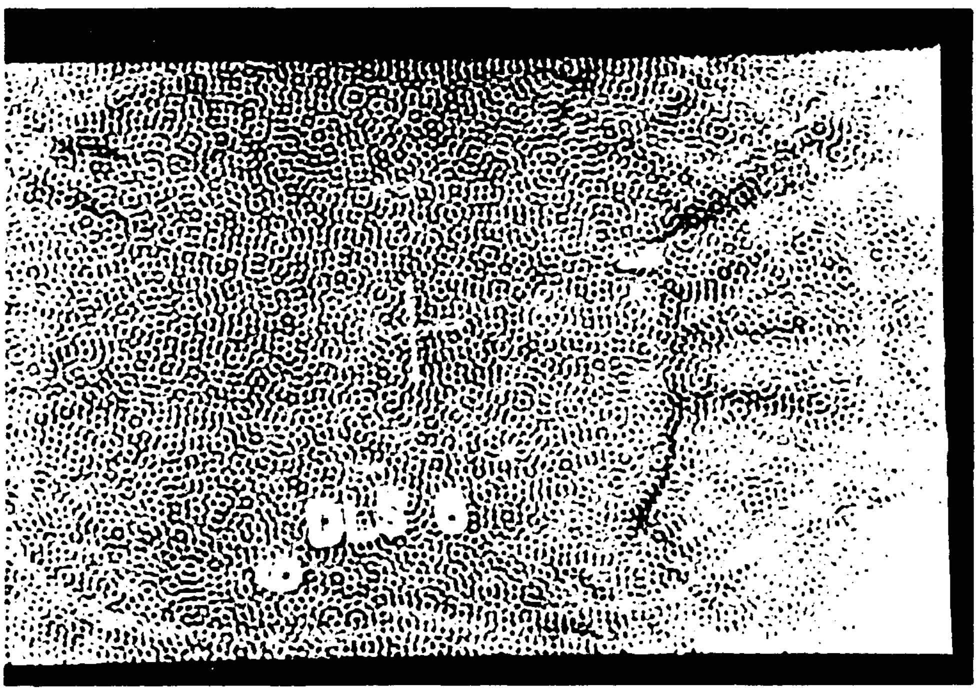


Figure 25. Radiograph of same section of helmet DLS-6 shown in Figure 25.

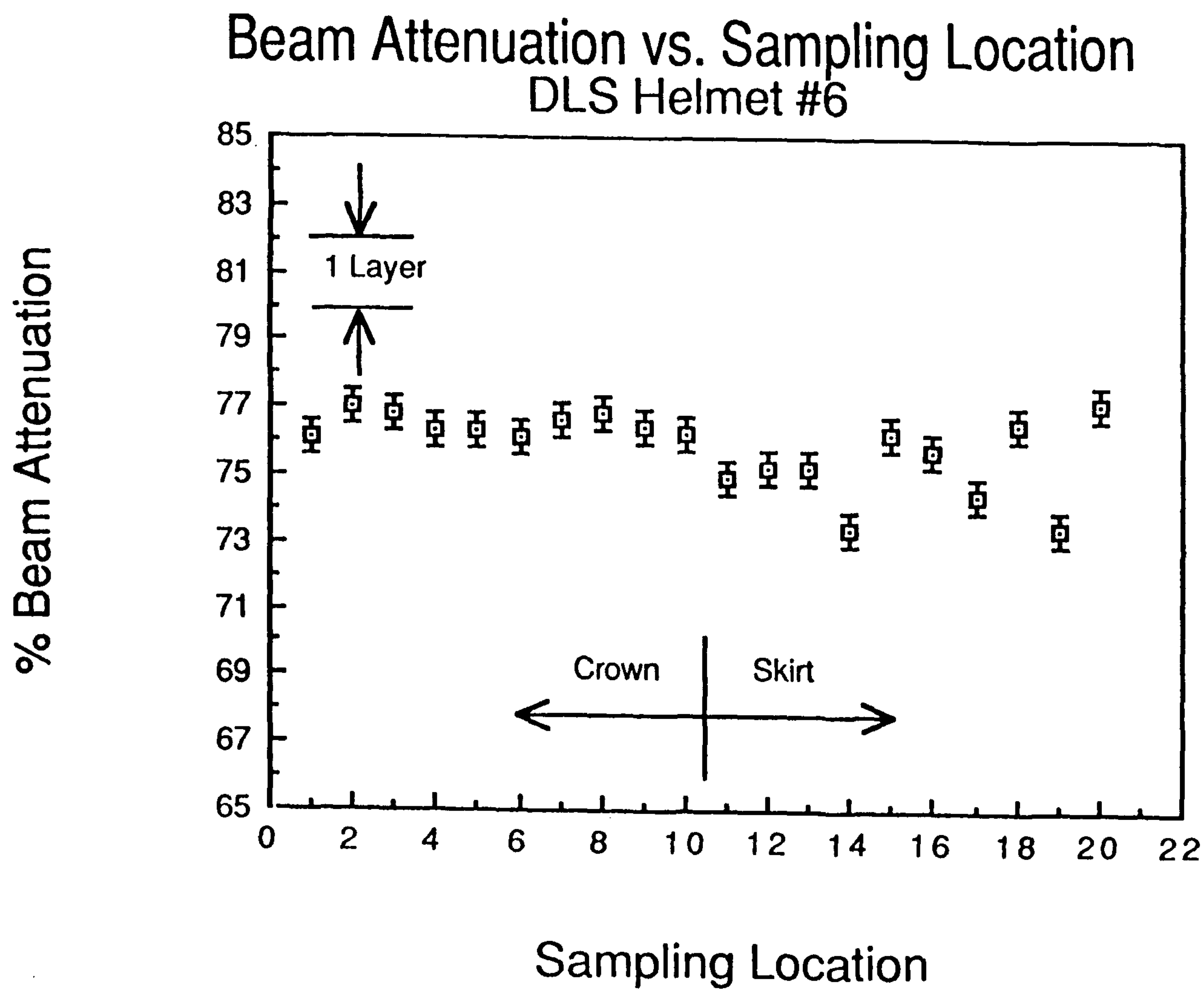


Figure 26. Beam attenuation for 20 sampling attenuation in crown and skirt regions of helmet DLS-6.

TABLE 5. Transmission of X-rays by Helmets.

Helmet Identification	Mean Transmission (Percent & Standard Deviation) Crown Regions	Skirt Regions
DLS-4	23.1 ± 0.2	22.6 ± 1.0
DLS-5	25.9 ± 0.4	25.2 ± 1.7
DLS-6	23.5 ± 0.3	24.8 ± 1.1
MEAN	24.2 ± 1.2	24.2 ± 1.1
UPI-1	26.1 ± 1.5	27.0 ± 3.0
UPI-2	26.2 ± 1.1	25.9 ± 2.6
UPI-3	23.9 ± 0.7	25.3 ± 1.3
UPI-4	25.3 ± 1.5	25.8 ± 1.9
MEAN	25.4 ± 0.9	26.0 ± 0.6
GEO-1	28.6 ± 0.3	28.6 ± 0.3
MEAN	28.6 ± 0.3	28.6 ± 0.3
GRAND MEAN	25.3 ± 1.7	25.7 ± 1.6
TOTAL MEAN	25.5 ± 1.7	

Five observers were asked to assign a "Darkness Value" (DV) between -4 and +4 to each marked sampling point in helmet UPI-1. A DV of +4 was to be assigned to an area on the surface of the helmet containing no visible indication of Kevlar cloth; a DV of -4 was to be assigned to an area containing no visible sign of resin. The minimum increment in DV to be used was 1. Examples of extremely resin-rich and resin-poor areas on the surfaces of helmets are shown in Figures 27 and 28, which are photographs of helmets UPI-1 and DLS-5. All DV testing was performed on helmet UPI-1.

The results of the DV tests are shown in Figure 29. The arithmetic mean (average) of the DV value of each sampling point reported by the five observers was plotted against the radiometrically measured beam attenuation. The attenuation and DV value were assumed to be linearly related. A straight line was fitted to the data points by linear regression methods and the correlation coefficient (R) was calculated. The calculated R value was equal to 0.68, which suggests a fair correlation between the variables. Computation of the reliability of R from the "degrees of freedom" of the test shows the probability that R has at least a 95-percent value. A value of R=0 would indicate no correlation; a value of R=1 would indicate perfect correlation.

CONCLUSIONS

Based on the findings of this study, it is apparent that the use of radiometric methods as developed by Reinhart and Associates is not well suited for determining the number of layers of Kevlar fabric in the U.S. Army Personnel Armor System Ground Troops (PASGT) helmet as currently manufactured. Problems with the resin/fabric ratio, paint thickness, and inflow of resin into voids and gaps prevents the system from accurately counting the number of layers of Kevlar.

The developed system is capable of determining the number of flat layers accurately under ideal conditions, as evidenced by the first set of tests. This was done using a 16 layer panel and adding 4 individual layers, one at a time and finding the attenuation coefficient. This was a controlled test, and did not take into account such variables as paint thickness or voids and gaps filled with resin.

Tests were done to determine the effect the helmet fabrication materials had on radiation attenuation. It was found that a 6.6 mil increase in paint on the surface or a 7.5 increase in the effective thickness of resin will mask the absence of one layer of cured composite.

The ability of the system to detect lateral gaps of 3/32-inch was investigated. Resin inflow, the flowing into a gap of resin from the surrounding prepreg during the manufacturing process, caused problems in detecting the gap. Only a 5 mil thickness of resin in the gap would destroy the ability of the system to detect the gap.

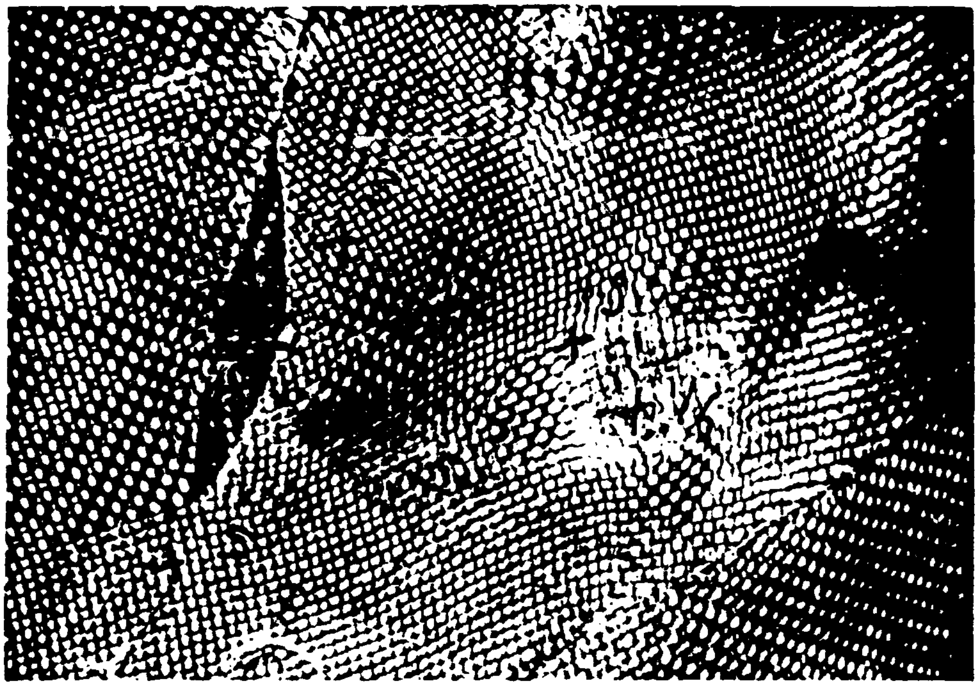


Figure 27. Close-up photograph of the interior surface of helmet UPI-1.

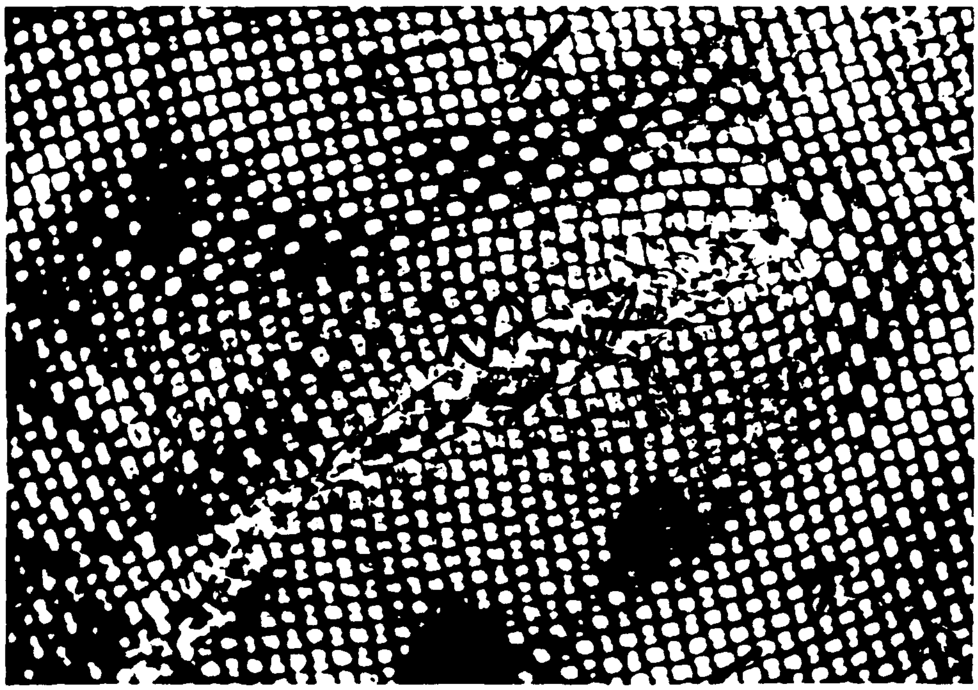


Figure 28. Close-up photograph of the interior surface of helmet DLS-6.

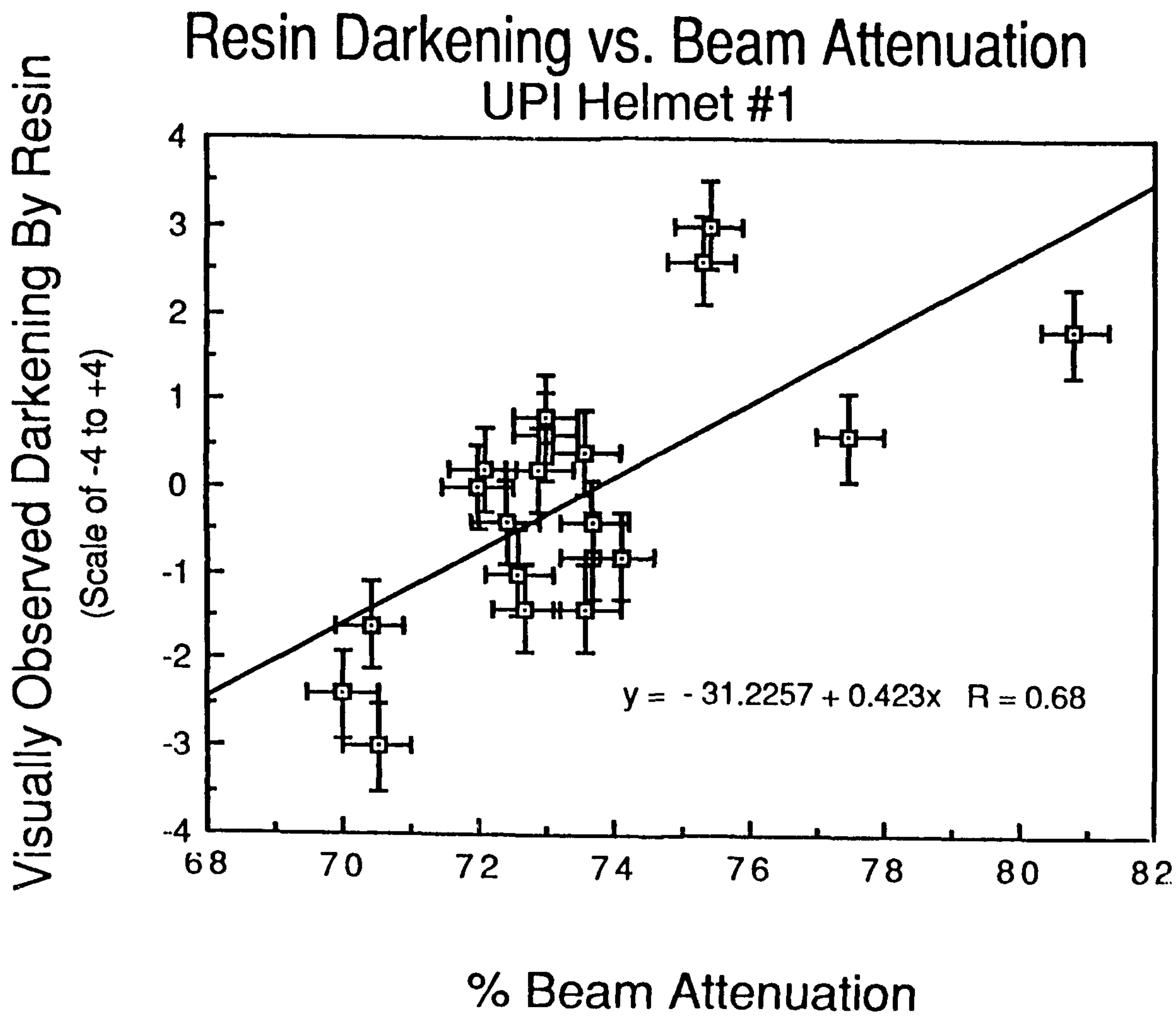


Figure 29. Correlation of resin darkening on helmet surface with X-ray beam attenuation.

It is for the above reasons that the system as developed is not well suited to accurately determine the number of layers of Kevlar fabric in the helmet. Voids and gaps in the layers filled with resin, variations in paint thickness, and variations in the resin/fabric ratio prevent the accurate determination of the number of layers of Kevlar at any one point on the helmet.

It was suggested that an averaging process be used to smooth out the data from a number of sampling points on one helmet. However, this will not satisfy the requirement that the system be able to determine the number of Kevlar layers at any particular point on the helmet.

RECOMMENDATIONS

It has been proven that the radiometric technique is responsive to selective changes in individual elements, yet the correlation\final acceptance tests based on the ballistic impact performance of the examined helmets. With these points in mind we make the following recommendations.

A comprehensive performance evaluation should be conducted wherein a statistically valid selection of typical production helmets is used as a basis for establishing realistic accept/reject criteria for Kevlar helmets. Such a program would typically involve a control group of not less than one hundred "acceptable" helmets plus a collection of rejected helmets made up of a minimum of 25 helmets representing each of the major perceived failure modes currently being used as a basis for helmet rejection. The evaluation of this statistical grouping should be conducted using the experimental protocols developed through the Phase I SBIR program in that the choice of radiation source and detection apparatus are considered optimum for the following study.

A comprehensive performance evaluation should be conducted wherein the statistically valid results of the above recommended study are carefully compared with the ballistic performance of the same set of helmets used in the above study. It is believed that the degree of correlation between helmets which failed the ballistic tests may have a higher correlation with the nondestructive radiometric result than found using currently subjective techniques based on largely superficial and cosmetic blemishes.

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